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SURFACE PREPARATION AND COATINGS
DESIGN/PRODUCTION INTEGRATION
HUMAN RESOURCE INNOVATION
MARINE INDUSTRY STANDARDS
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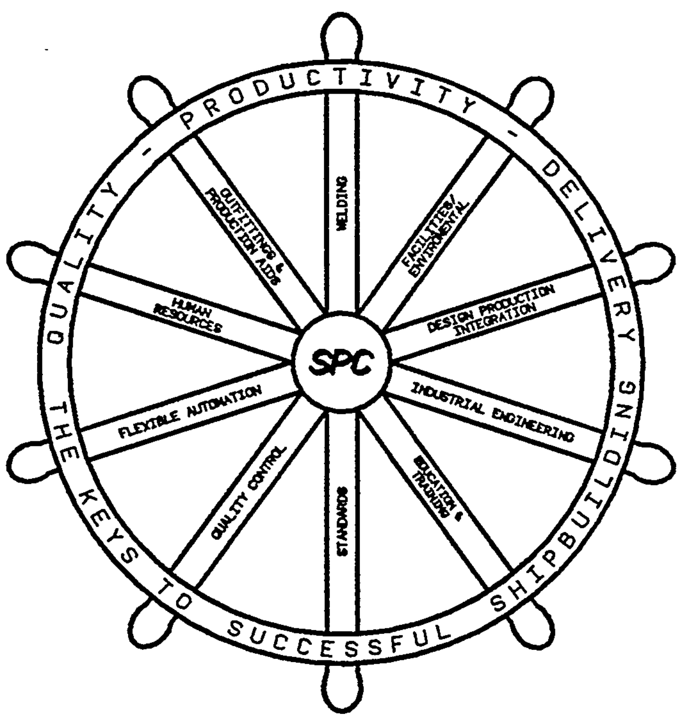
1993

SHIP PRODUCTION SYMPOSIUM



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CENTENNIAL
1893-1993

Williamsburg Virginia, November 1-4, 1993

F O R E W O R D

This volume contains the texts of the twenty-five technical papers presented during the National Shipbuilding Research Program's 1993 SHIP PRODUCTION SYMPOSIUM, sponsored by the Hampton Roads Section of the Society of Naval Architects and Marine Engineers (SNAME).

The Symposium was held at the Williamsburg Lodge in Colonial Williamsburg, Virginia, from November 1-4, 1993. This marks the second time the Hampton Roads Section of SNAME has hosted the Symposium in Williamsburg.

The Symposium theme was "Keys to Successful Shipbuilding-Quality, Productivity and Delivery. " The mission of the National Shipbuilding Research Program is to assist the U. S. Shipbuilding and Repair Industry in achieving and maintaining global competitiveness concerning quality, time, cost and customer satisfaction. The specific goals for the 1990's are; reduce construction and repair process times while reducing cost to design, build and repair ships; promote a commitment to quality and customer satisfaction; obtain a three percent share of the global shipbuilding market and to become the nationally recognized forum to advance shipbuilding and ship repair technology.

The technical papers presented during the 1993 SHIP PRODUCTION SYMPOSIUM covered a diversity of topics which supported this year's theme and will affect schedules and costs dramatically over the next decade.

As Chairman of the Steering Committee, I wish to thank all committee chairmen and committee members who worked so diligently to make the Symposium a success. And, on behalf of the Hampton Roads Section of SNAME, our sincere thanks are extended to all those who supported the Symposium as authors, moderators, attendees, and financial contributors.

M. Roger Eshelman
Chairman, Steering Committee

1993 SHIP PRODUCTION SYMPOSIUM
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The National Shipbuilding Research Program
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The Design of Longitudinal Beam Layout On A Curved Shell Based on the Production-Oriented Design Concept

Kohji Honda (V) and Noriyuki Tabushi (V)-Kure Shipyard, Ishikawjima-Harima Heavy Industries Co., Ltd.

ABSTRACT

A VLCC (Very Large Crude oil Carrier) has approximately one thousand curved longitudinal beams, many of which have three-dimensional complicated curvatures. Due to the shortage of highly skilled workers and the need to keep costs down, production and structural designers have worked to reduce the number of such beams.

In order to meet the requirements of production, IHI (Ishikawajima-Harima Heavy Industries Co., Ltd.) has attempted several design approaches for the longitudinal beam layout, to reduce the number of beams that have complicated curvature. Recently, through the application of a Computer Aided Design (CAD) system, which has been improved for shipbuilding based on the Calma's system, a new design method for the longitudinal beam layout has been successfully developed. A significant number of the beams with a twisted configuration were eliminated, and replaced with beams of simpler, two-dimensional shapes.

This paper shows the transition of these design approaches, and the application of the new design to building a VLCC.

INTRODUCTION

In a layout design of a longitudinally framed ship, represented by a VLCC, the longitudinal beams on the curved shell usually have a complicated configuration. These beams have three kinds of curvatures : single plane, out of plane, and axially twisted curvatures (Figure 1). These curvatures are formed in two steps at a bending shop. At the first step, the beams are cold formed on a single plane by a bending machine (Figure 2). And at the next step, they are bent out of plane and twisted at the same time by line heating (Figure 3).

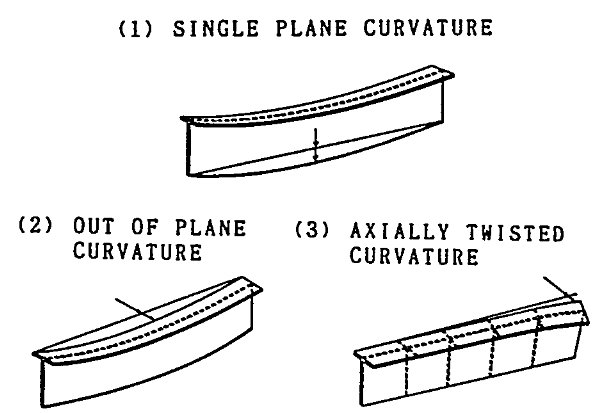


Figure 1. Three kinds of curvatures of longitudinal beams on a curved shell

Figure 2. Bending work by cold bending

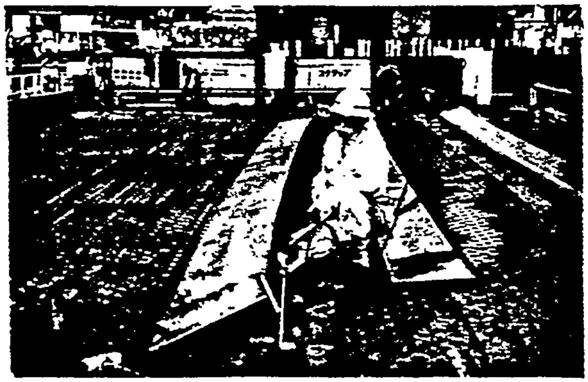


Figure 3. Twisting work by line heating

The line heating method needs skilled workers. Recently however, the number of them in the Japanese shipbuilding field have been decreasing rapidly. In order to keep productivity, quality and safety in the production shops, it is important to emphasize the production-oriented design concept. Several design approaches have been attempted for the purpose of reducing the number of longitudinal beams that have complicated curvatures.

TRANSITION OF THE LAYOUT DESIGN OF LONGITUDINAL BEAMS

The Conventional Layout Design

Essentially, the longitudinally framed layout was determined in the functional design stage. Then, in the primary layout design stage, longitudinal beams were laid to be most effective for the longitudinal strength of whole ship. That is, the beams were laid across frame lines almost normally in the body plan drawing, and were fitted normally on the shell plate (Figure 4). In this design approach, longitudinal beams on the curved shell had complicated configuration. Too many man-hours had been spent on the fabrication of these beams.

The Modified Layout Design

Thereafter, in order to facilitate block positioning at the erection stage, block seams were laid horizontally. The longitudinal beams were also laid horizontally in the body plan drawing, so as not to cross with a seam line (Figure 5). At the same time, the fitting angle of longitudinal beams was made uniform to reduce twisting work by line heating. But in this design, out of plane bending work still remained, and this bending work was usually performed with pulling tools in the fitting process at the assembly stage of a block. Also, longitudinal beams, which required twisting work, were concentrated to a few blocks; this helped to reduce the number of twisted beams.

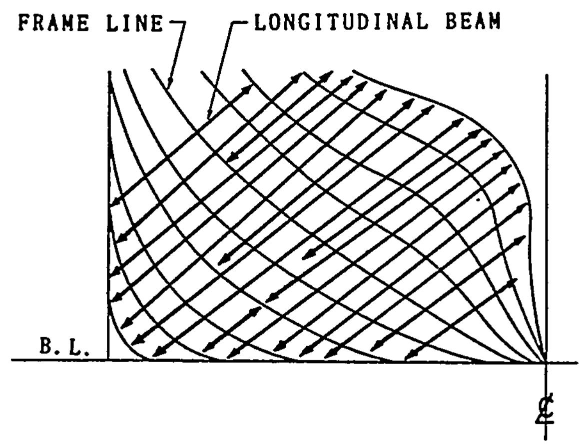


Figure 4. The conventional layout design

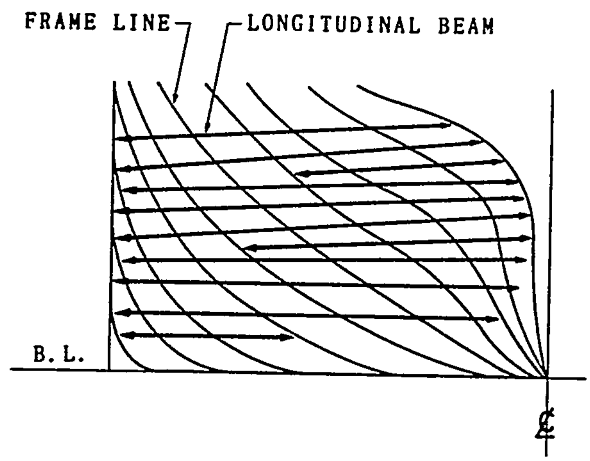


Figure 5. The modified layout design

The Advanced Layout Design

The best design for production was for the longitudinal beams to be laid on a single plane because these beams have neither twisted nor out of plane curvatures (Figure 6). In such a design, longitudinal beams should be treated as planes in three-dimensional space. This is difficult to show using conventional design methods, based on body plan drawings with two dimensions. However, such a layout of longitudinal beams can be designed easily with the proper application of a good CAD system.

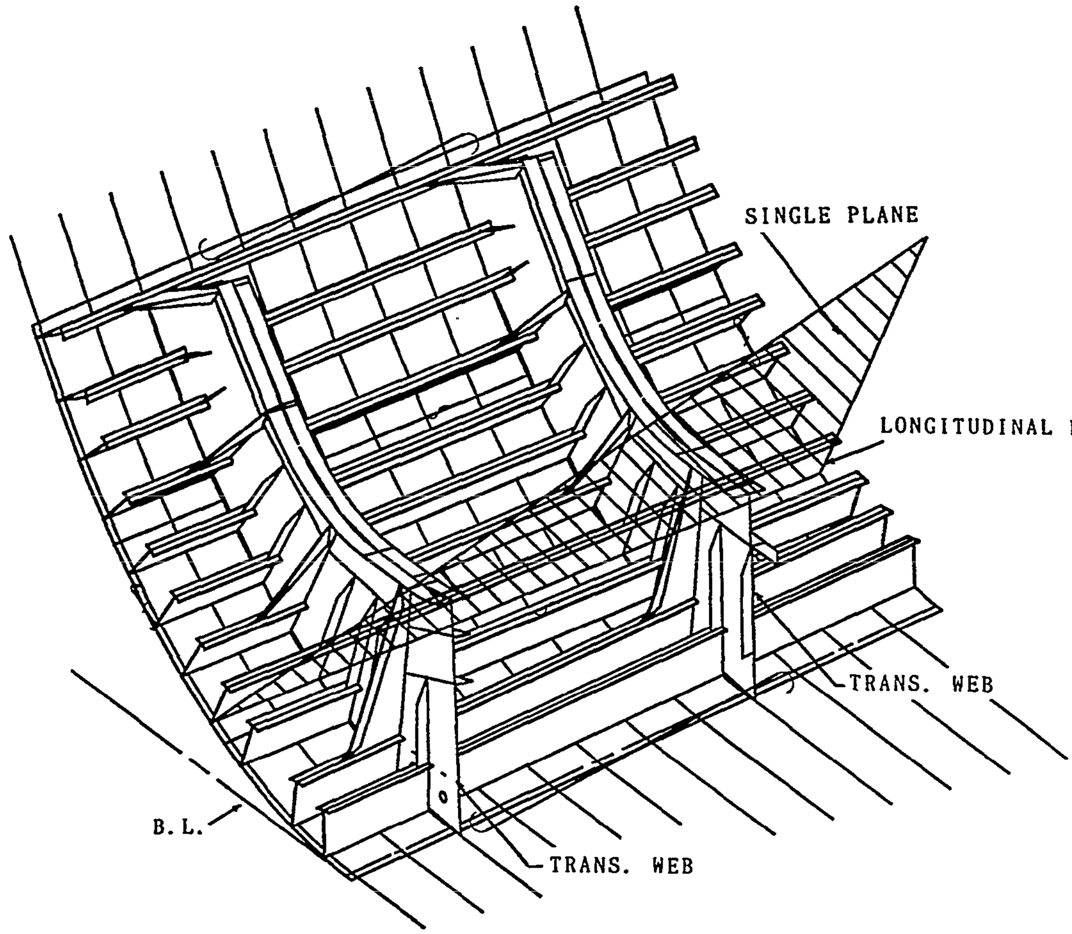


Figure 6. Example of longitudinal beams laid on single plane

DEVELOPMENT OF THE ADVANCED DESIGN METHOD OF LONGITUDINAL BEAM LAYOUT

The method of longitudinal beam layout design was improved along with the improvement of the computer system. At first, the batch system for the conventional layout design method had been developed and applied by the shipyard. At that time, the fitting lines were designed as straight lines in the body plan drawing. The operator input the coordinates of both end points of the lines, and the fitting angle of beams at both the end points. Then the operator verified the space between any two longitudinal beams, and the variation of fitting angles of beams to shell plates in the output drawing.

Thereafter, in order to improve the efficiency of the ship production design, the three-dimensional CAD system was developed. This CAD system has been applied to the layout design of longitudinal beams in the shipyard since 1986. The modifications of the space and angle of beams have been interactively carried out in the body plane view on a CAD workstation.

Using this CAD system for the advanced layout design, the fitting lines of longitudinal beams, which have only single plane curvatures, are easily given as the intersection lines of shell plate surfaces and planes on which the beams are laid. The given fitting lines are bent, not straight, in the body plan view (Figure 7).

But the application of the advanced design method of longitudinal beam layout created new problems at block butts (Figure 8):

1. The joints of longitudinal beams were slightly knuckled.

2. The corners of web and face plate of longitudinal beams were slightly deformed out of square at the joint.

Therefore, the CAD system was improved to solve the new problems interactively on screen. In order to obtain such a function, it was very important to create the three-dimensional digital mock-up in the CAD system. In the improved CAD system, the shapes of longitudinal beams were created as surface models along their shell plate fitting lines along with their attributes (scantlings and fitting angles) (Figure 9). Then, using surface models of the longitudinal beams, the modifications of knuckled angles and deformed corners of web and face plates at joints were carried out interactively.

In addition to improving the CAD system, the batch system for parts generation has been improved. This corresponds to correction of the joint deformation of the beams at block butts.

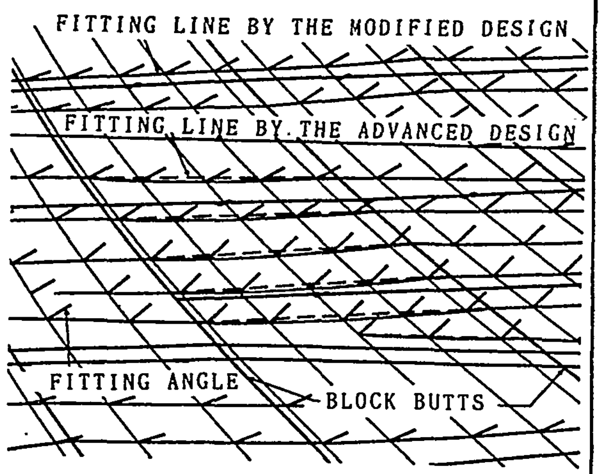


Figure 7. The comparison of the advanced design with the modified design

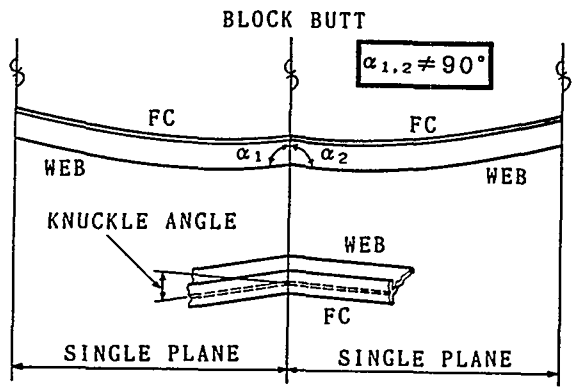


Figure 8. The new problems at block butt

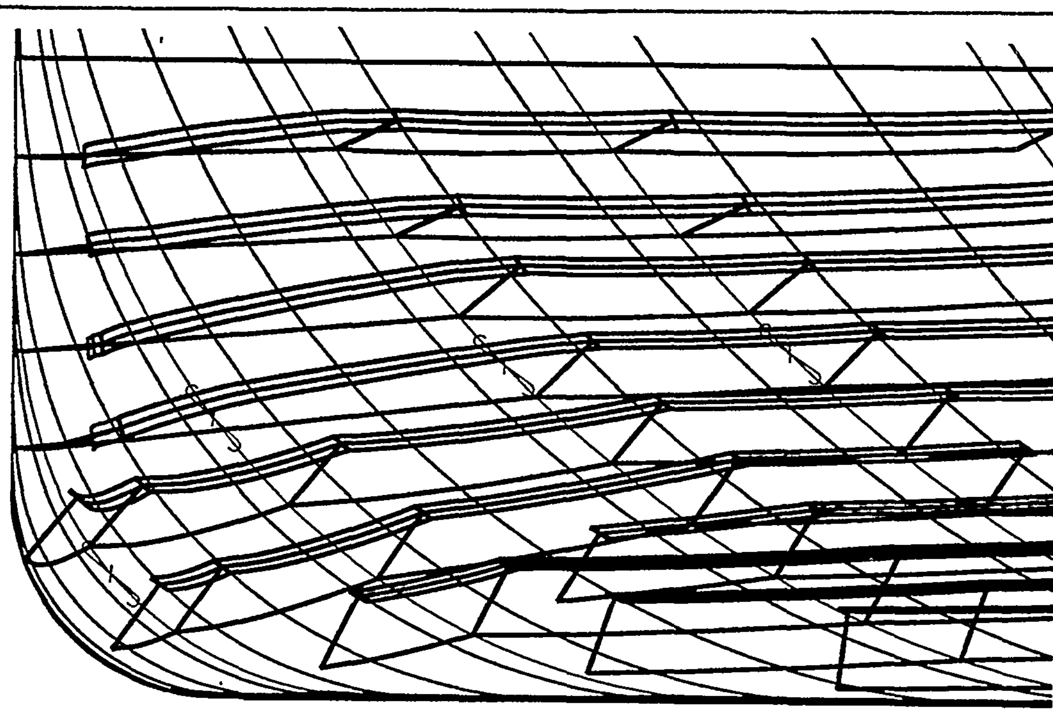


Figure 9. Surface models of longitudinal beams

CONSIDERATION FROM A STRENGTH POINT OF VIEW

To use the advanced layout design of longitudinal beams, several strength verifying calculations were carried out to justify the design change.

The space between any two longitudinal beams should be kept as close to the planned value as possible. If the space is too large, the local strength of the panel, comprised of the shell plate and longitudinal beams, will not be enough. If the space is too small, it will be difficult to control hull weight and workability at production.

The fitting angle of the longitudinal beam to the shell plate should be kept as close to 90 degrees as possible, so as not to reduce their local bending strength (i. e. their sections modulus with the shell plate). The range of possible angles is limited from 70 to 110 degrees for the beams with T shape section in the design standard. At 70 and 110 degrees, about 10% of their strength is lost, compared to the strength at 90 degrees (Figure 10).

The longitudinal beam knuckle joint at block butts is subject to local lateral deformation between transverse web frames from the stress component of a ship's longitudinal bending moment. The efficiency of longitudinal beams, which are knuckled 10 degrees at the joint, is reduced to about 70% of the efficiency at the full strength condition. But the advanced layout design is applied to side beams only on curved shell blocks, where the working stress by the ship's longitudinal bending moment is rather small. So it is considered that the influence of such reduction of strength is negligible.

Evaluating the local strength of the beams, the local bending moment is considered small at the knuckle joint as the block butt is located at about 1/3 distance of the transverse web frame spacing (Figure 11). The effect of the local bending moment is negligible.

APPLICATION TO VLCC BUILDING

In 1991 the advanced layout design of longitudinal beams was applied to the building of a VLCC in the shipyard for the first time. The following design policy was used.

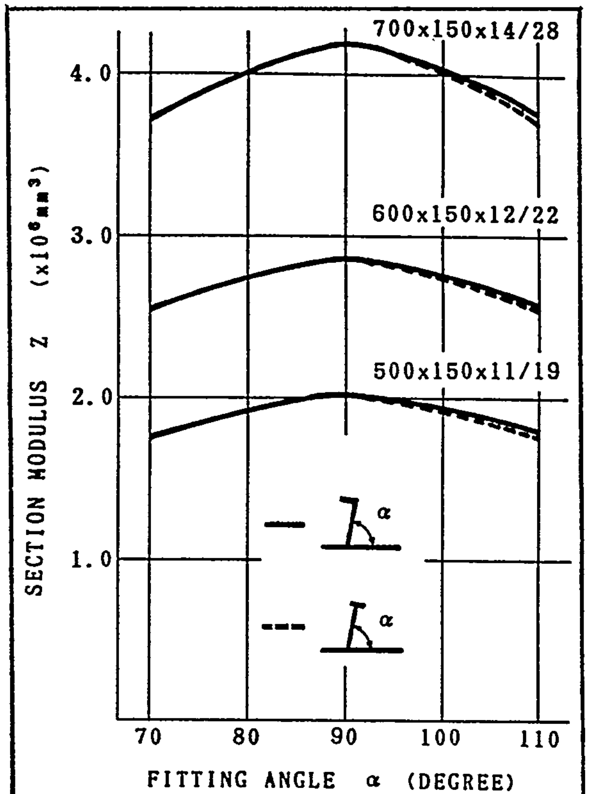
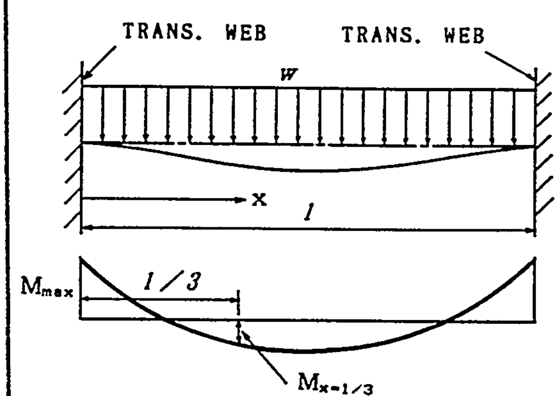


Figure 10. Section modulus of L and T shape section with plate 610 x 15 (mm)



$$M_{x=l/3} = -\frac{w\,l^2}{36} = -\frac{1}{3}M_{max}$$

Figure 11. The local bending moment diagram working on a longitudinal beam

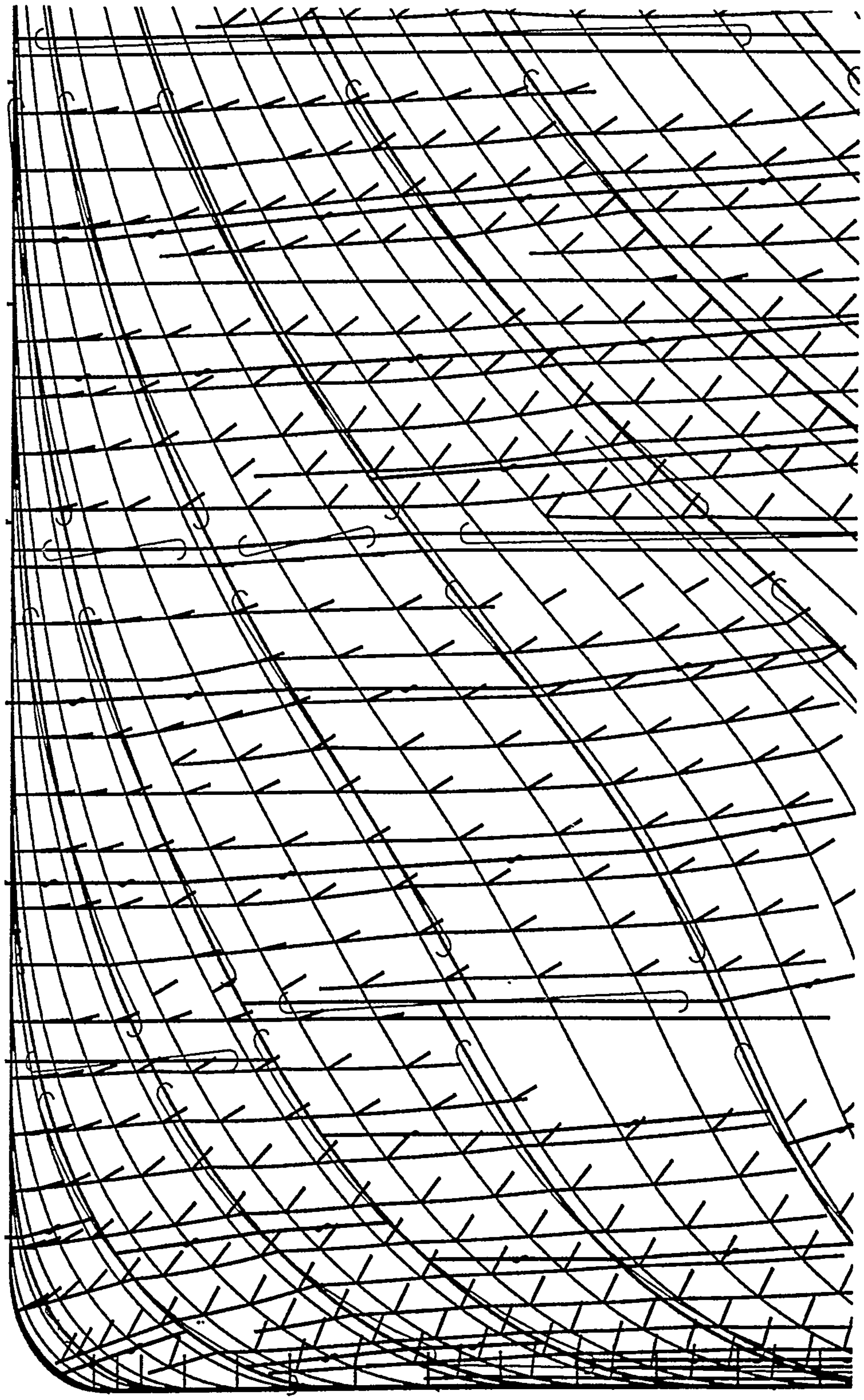


Figure 12. A part of the structural lines drawing of the VLCC applied the advanced layout design

1. Longitudinal beams were laid horizontally as often as possible in order to lessen the knuckle angle of beams at the block joint, because an increased knuckle angle enlarges the bending moment. The knuckle angle had to be less than 8 degrees.

2. The fitting angle of a longitudinal beam to the shell plate had to be larger than 70 degrees and smaller than 110 degrees.

3. Longitudinal beams with curvature in only a single plane were used as often as possible. Where a twisted curvature could not be avoided, the beams were shaped through line heating.

The latest VLCC has 950 curved longitudinal beams in the whole ship. The number of single plane curvature beams by the modified layout design was about 490. By applying the advanced layout design to the remaining curved beams, about 220 beams of complicated curvature were eliminated and replaced with beams of single plane curvature. As a result of this improvement, only 244 beams of twisted curvature remained (Figure 12).

EXPECTED EFFECTS OF THE ADVANCED LAYOUT DESIGN

In addition to the expected man-hour saving in the bending work of longitudinal beams at the bending shop, there are other effects of the advanced layout design.

Accuracy in fabrication of the longitudinal beams is improved because increased quality of single plane curvature beams contributes to fabrication of beams by a bending machine without heating.

At the assembly stage, the installation of longitudinal beams, which have neither out of plane nor twisted curvatures, saves fitting work of beams to a shell plate, and improves dimensional accuracy of the assembled curved block (Figure 13).

Then, at the erection stage, accurately fabricated joints of the block butts make the connection work easier, and man-hour is saved (Figure 14).

CONCLUSION

In today's labor market, where numbers of skilled workers in shipbuilding are decreasing, mechanization of production processes contributes to improved productivity. In this respect it is important to attempt approaches based on the production-oriented design concept. A simplified hull structure facilitates production work, and encourages mechanization of production equipment in a shipyard.

Such approaches, based on the production-oriented design concept, require the efforts of shipyard management in cooperation with production engineering, design and computer system departments.

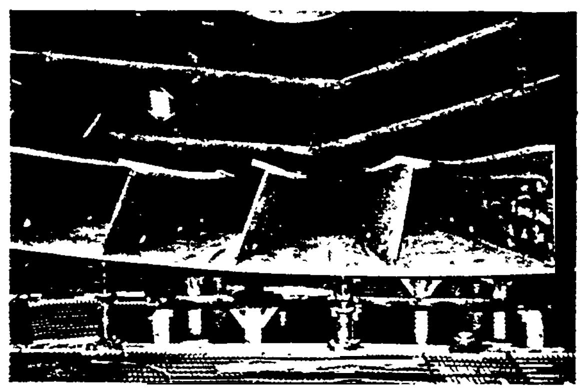


Figure 13. The block with applied advanced layout design

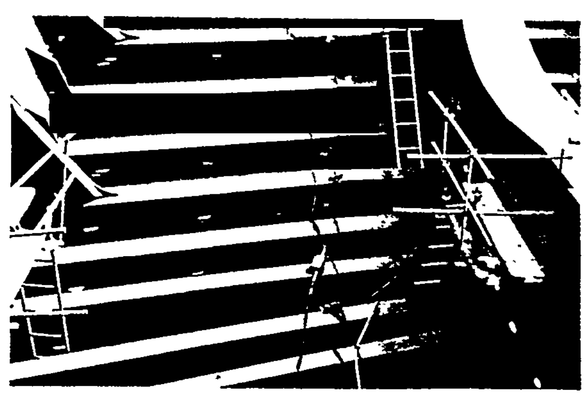


Figure 14. The block butt with applied advanced layout design

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Production Integration Via Solids Modeling

E. K. House DeVale (V) and J. R. Guilbert (V)-Newport News Shipbuilding

ABSTRACT

The integration of production planning within design has had a positive impact on both the design process and the design products. To effectively accomplish the integration, it is necessary to have a single 3-D product model of the ship, by which all design disciplines and construction planning personnel can effectively communicate.

The authors will address the significant changes this new approach has upon the design community and its deliverables. They will provide an overview of the enabling technologies and methods which facilitate construction-oriented feedback in the design phase. They will review additional benefits derived from the product model, such as eliminating physical mock-ups.

INTRODUCTION

The ship design/ construction industry has made significant improvements in efficiency over the last twenty years. The driving force was the fight for survival by individual yards in a shrinking market for new design, construction, and repair contracts. This condition has recently become even more critical for domestic yards as the U.S. Navy reduces ship acquisitions. This increased competition is forcing dramatic changes in the ship design and construction processes. An example of this trend is the use of computerized drafting tools to increase the accuracy and consistency of design products. On the construction side, modularizing large sections of vessels, and employing zone technology are streamlining the construction process, and reducing the amount of time required from keel-laying, to launch, to delivery. In both areas these methodologies are employed to drive down costs and increase efficiency. Generally within the industry, these innovations have been implemented through an isolated, rather than a coordinated effort.

During the last ten years industry leaders have recognized that a key to improving efficiency is to break down the barriers of isolation between the design and construction organizations. The term “concurrent engineering” is used to describe the incorporation of manufacturing intensive information into the design process. The aim is to reduce total cost and time associated with transforming design parts

into manufacturable parts.

Before solids modeling systems were available, the integration of design and construction was limited to the examination of mature design products, and the attempt to repackage the data for production. Generally, feedback concerning these design deliverables in the design office was filtered or ignored, due to the high cost of reworking the design product. Despite significant construction input, many potential improvements in efficiency were not implemented because of the limitations of the medium. However, the availability of computer-based, solids modeling design systems is changing the paradigm. Properly applied solids modeling allows parts to be examined before committing them to drawings. This provides an opportunity for a producibility review prior to preparation of drawings or other manufacturing data. Thus, production integration via 3-D solids modeling facilitates addressing construction concerns within the design phase of a project.

Within the topic of production integration via solids modeling, there are numerous areas for discussion. This paper focuses on production integration in the design of SEAWOLF, SS(N)21. The SEAWOLF project is a significant case study because it is a large-scale project with a complex design. In order to give the necessary background on the medium used for the integration, the authors explain the basic characteristics of the 3-D, solids modeling system. Then, the paper discusses; (1) the use of 3-D, solids modeling for producibility, (2) the integration process in the SEAWOLF project, (3) the altered design deliverables, and (4) future applications.

3-D MODEL FEATURES

The major advantage of integrating production planning into the design phase is that manufacturing and construction concerns may be addressed prior to drawing development. In order to successfully perform this function, production planners must have access to the complete and current design. Completeness is critical because part interactions, accessibility, and interferences are the salient issues in production integration. A modeling system that reflects changes as they occur allows planners and designers to make decisions before change becomes too difficult. Traditional design tools and deliverables are inadequate for supporting such an integration. Solids modeling is the technology employed in the integration of production planning in the SEAWOLF design. In particular, the Newport News Shipbuilding (NNS) developed modeling system VIVID® is the tool selected to arrange structure, distributive systems, stowage, and machinery within the hull of SEAWOLF.

This solids modeling system was first employed in the modularization of SSN 756 in 1984. More recently, the system’s unique capabilities have been applied to many commercial, U.S. Navy and foreign navy projects. NNS is one of several companies in various industries using a 3-D modeling system to help integrate production concerns

into the design process. In the shipbuilding and design industry both Bath Iron Works and Ingalls Shipbuilding experimented with a CAD/CAM model in the design and construction of the DDG-51 and the SA’ARs, respectively(l)(2). In the aircraft industry, Boeing is using a 3-D, computer aided design (CAD) environment and a design/build team concept for incorporating manufacturing concerns into the design of the 777 twinjet transport. These efforts are being employed to reduce costly errors, changes, and rework (3).

The requirement for access to the complete and current design is handled in this solids modeling system by storing parts for the entire vessel in a single database. Each physically significant part in the ship is modeled, topologically connected, and instanced in its ship location in the database. As a result of this comprehensiveness, designers and planners can perform their duties understanding the relationship each part has to the rest of the model. Understanding the design configuration for all the systems in a given area allows production planners to formulate a build strategy, document it within the model, and appraise parts for producibility before commission of the data to drawings. These steps result in superior quality source data for drawings, and maximized producibility of design parts.

Although the 3-D modeling system incorporates parts from the different disciplines, and illustrates their interactions and interferences, each part class is handled differently. Within this 3-D modeling system, the pipes, fittings, cables, wireways, ventilation, plates, holes, components, and beams are modeled, stored, and handled uniquely based on their type. In other words, functions or attributes are restricted to certain part types. The attributes of geometry are those characteristics that give the parts their physical identity. For example, the model creates and stores plates by material type, thickness, and square footage. Piping attributes include material type, inside and outside diameter, bend radii, and minimum design wall thickness. Each part class has a dedicated set of characteristics that the model stores, plus the basics such as part number and location within the ship. Functions permitted on the part classes match the characteristics of part geometry. For example, in ventilation modeling, sectioning bends allows a part bend to be approximated by a series of straight sections rather than a smooth curve. This function is permitted for ventilation because round, oval, and transition curves are fabricated using a section approximation. However, sectioning is not permitted for pipe since pipe bending results in a smooth, even radius curve. This translates the characteristics of the “real” part to a corresponding modeled part.

A majority of modeled parts derive their configurations from referencing components stored in a catalog. There are approximately fifty thousand components in the SEAWOLF design catalog, all of which have a “true” detailed representation. The catalog is

an important feature because it allows a detailed representation of a part to be stored once and referenced many times within the model. If a component vendor changes a part's characteristics, this change can be reflected throughout the ship design by merely updating the catalog, rather than manually updating each reference. The accuracy of the SEAWOLF catalog and parts in general is critical because of the tightness of submarine design. The criterion for component modeling is to hold interface points to exact dimensions, and other surfaces in SEAWOLF to an accuracy that deviates less than 0.8 mm (1/32 in). The resulting images are complete and accurate, and provide the user with a true representation of the ship space upon which to base design and construction decisions.

Using a single database for the complete design also facilitates retrieving current information. Current in this case means up-to-the minute; there is no "down-time" for interfacing different segments of the design. Within this software system, the 3-D model can be modified interactively by many users at the same time. The users can be from different design disciplines or production planning. Capturing the changes as they are made allows other users to respond to the modifications in a real-time environment, thus reducing rework and invalid designs. The software also has a feature for reporting all parts that have changed since a given date, and parts impacted by those changes. This feature is useful in tracking design modifications. With approximately 453,000 parts modeled for SEAWOLF, managing concurrent changes is a critical task.

PRODUCIBILITY

Addressing production planning concerns in the design phase of a project through 3-D modeling provides considerable benefits. In its application within the 3-D modeling, producibility is the ability to produce or manufacture a modeled part to specification. One goal of integrating production planners into the design process is the elimination of parts which cannot be fabricated from the model, and therefore the drawings, initial graphics exchange specification (IGES) data, and any other design products generated from the model. This filtering is achieved through several methods. In addition to incorporating production knowledge, the modeling system provides three separate features to eliminate unproducible parts from the model. They are tests, tools, and interactive feedback. In general, all of these features measure and/or accept parts based on producibility. Producibility testing depends on the part definition; the more specifically a part is defined, the more thoroughly it can be checked for producibility. Since each physically significant part for SEAWOLF is modeled, the producibility checks for parts in this design are rigorous.

Tests

The software tests have encoded definitions of

SHAPE 18 (PROGRAMMING DATA)

FIND NO.	ASSY NO.	MATERIAL TYPE	MATERIAL THK	DATA W	D	W1	D1	L	V	X	X+/-	Y+/-				JOINTS OL/BUTT	AIR FLOW U/D	NO. CUT OUTS	NO. PCS	SEAMS P/W	REMARKS
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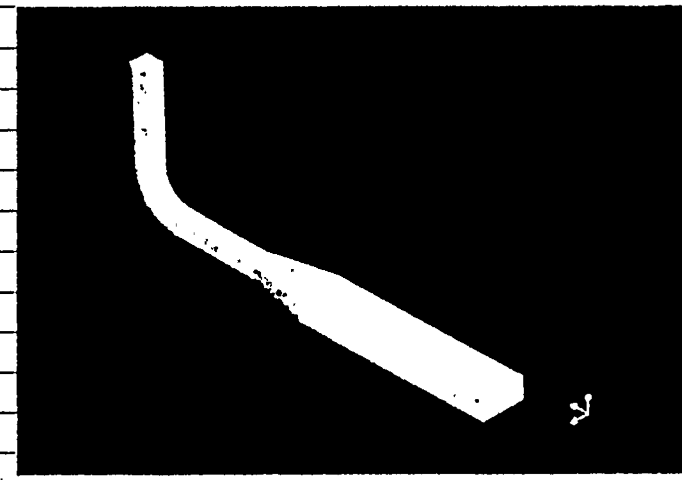
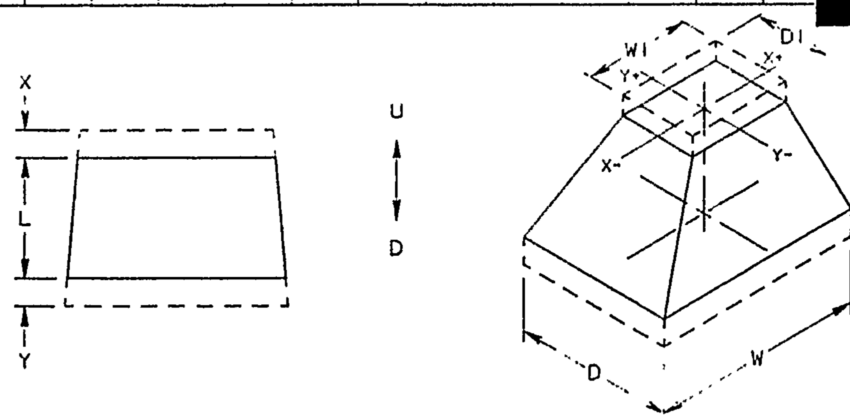




TRANSITION - RECTANGLE

FIGURE 1

acceptance conditions for various part classes. An example of the utility of these tests can be shown in ventilation modeling for SEAWOLF. Traditional design agent ventilation drawings depict "runs" instead of individual ventilation parts. A traditional ventilation drawing shows point-to-point transits with no individual part definition. The SEAWOLF specifications dictate the development and issue of detailed ventilation parts on the drawings. Over 90% of SEAWOLF ventilation parts conform to a set of industry standard shapes. When modeling ventilation in the 3-D product modeling system the designer can automatically check for compliance with the standard shapes. The drawings translate the modeled ventilation into a list of discreet parameters needed to fabricate each ventilation part (Figure 1). This testing process has two major benefits: the first is fostering the use of standard ventilation shapes which maximize producibility, and cost effectiveness. The second benefit is the automatic selection of the most producible of the standard shapes. For conditions where multiple shapes may be used, the parameters for the most cost effective shape are calculated and transferred to a drawing sheet.

Tests are provided for other part classes as well. For example, piping design includes checks for normal connectivity, and bending machine compatibility (Figure 2). These tests prevent rework costs associated with drawing revisions and scrapped material. Cables,

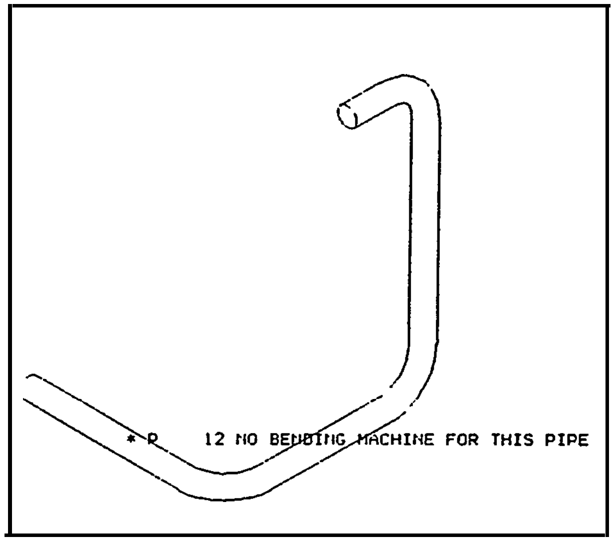
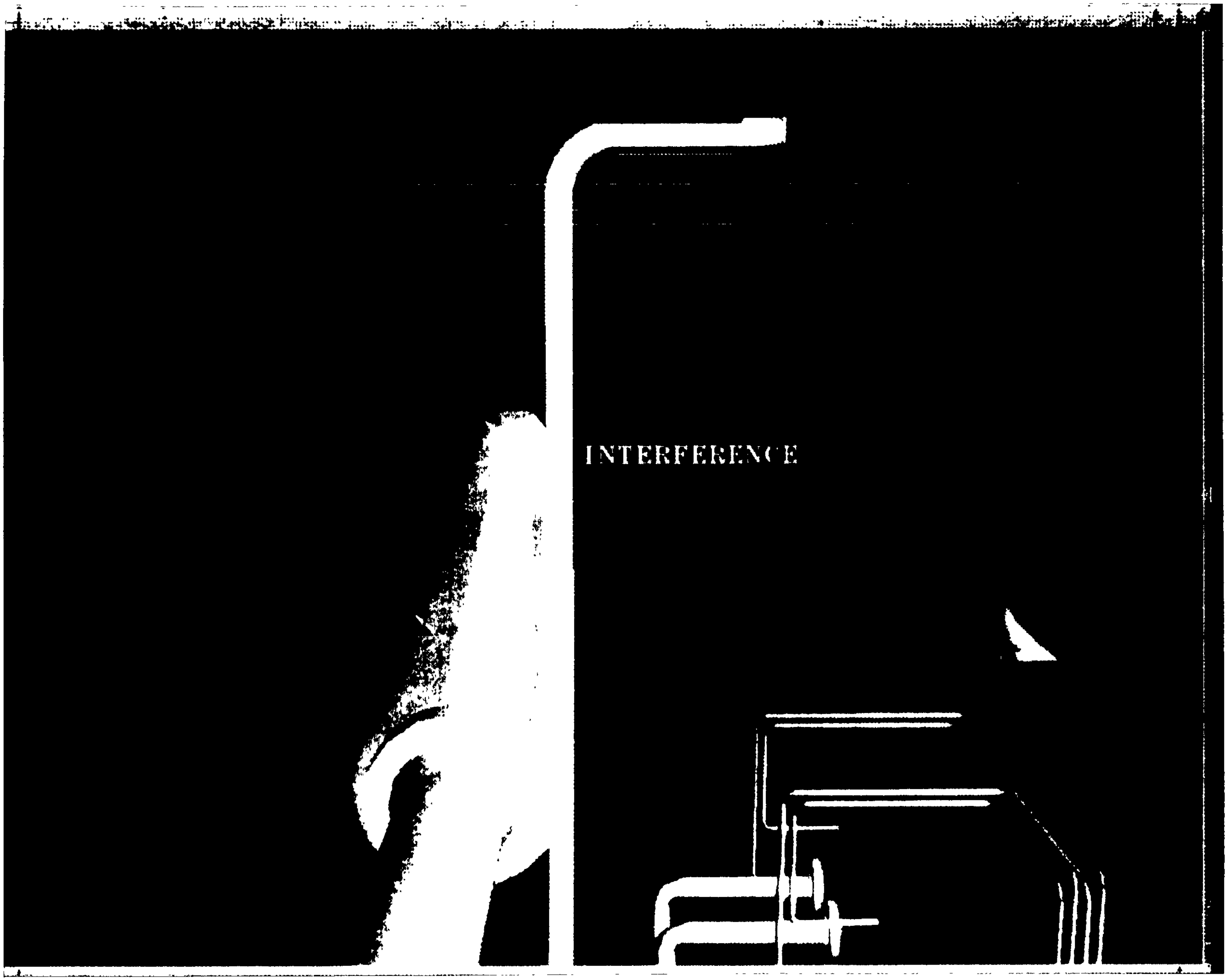


FIGURE 2

structure, and sheet metal have their own-specific tests, and the potential for designing new tests to match potential production limitations exists.

Tools

Tools are also important instruments for the designer to wield in determining if a designed part is producible. Unlike the tests which have embedded intelligence about acceptance conditions, tools are aides for the designer to use in evaluating the modeled parts. For example, the 3-D modeling system provides the designer the capability to grow parts and to perform interference analysis on grown and adjacent parts (Figure 3). The growth feature expands a part by a given amount. The interference analysis is an easily performed and accurate check for parts that physically occupy the same space, or encroach into access spaces needed for operation or maintenance. In submarine designs, noise clearances are an additional factor. The solids modeling system employs


INTERFERENCE

an expert system to identify noise interferences and to preserve shock excursion models.

In addition to the benefit these features provide for the designer, production planners use these same tools to identify instances of tight tolerances. By identifying areas of tight tolerance during design, they are able to relate to the builder, via construction drawings, where more accuracy in fabrication and/or installation is necessary. Providing this kind of detailed tolerancing data has only been possible since the advent of 3-D modeling technology. It is perceived that the net result will be a reduction in construction rework costs for correcting interferences as a result of tolerance stack-ups.

Interactive Feedback

The tools and tests described above operate after the part has been defined. The timing of interactive feedback is different; it happens while a part is being defined. Depending on the seriousness of the infraction, the system will either deny the user the ability to define a part, or simply display a warning message. On the least serious side, the system warns modelers if they duplicate part names while designing parts. The more serious interactive feedback is for infeasible geometry, such as a plate not defined on a plane, or an incompatible bend radius for pipe, ventilation or cables. The immediacy of the feedback allows the modeler to alter the part definition while still focused on the particular part. This again prevents the issuing of defective parts on drawings, and ultimately preventing rework in design and construction.

Interactive feedback, designer tools, and automatic tests work together to eliminate parts which cannot be fabricated from the model, and hence the design products. They are adapted to provide production-oriented guidelines, and are tailored to each specific part class. The result is lower rework costs associated with production due to the identification and correction of serious design flaws before committing the design to a drawing.

CONCURRENT DETAIL DESIGN AND DETAIL PLANNING

The shipyard’s most comprehensive use of solids modeling is as lead design yard (LDY) for the SEAWOLF class attack submarine. This role charges the LDY with the responsibility for detail design and arrangement of the forward compartment. This design effort provides the first large-scale opportunity to integrate production planning with design by the use of the community 3-D model. In contract design, the U. S. Navy established producibility requirements which dictate a design process which allows the design to be equally accessible to both designers and production personnel. The advantages of a computer modeling solution are further amplified by the detail design specifications, which dictate a design agent-developed construction plan, and corresponding product-oriented construction drawings, called

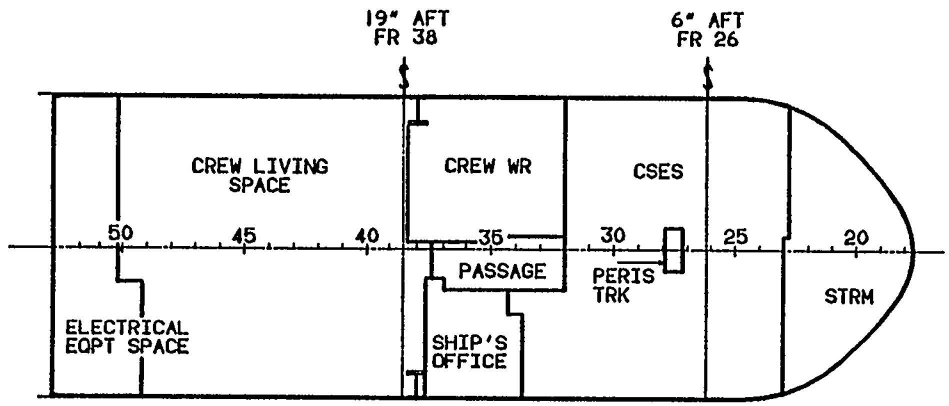
sectional construction drawings (SCDS). In order to satisfy the specifications the LDY committed to model its part of the design completely within the solids modeling system, and to staff the design effort with a team of experienced shipbuilders from waterfront trades. The success of the effort depends on the ability to integrate the production planners into the design process, rather than relegating them to reviewing completed design products.

Contract Design

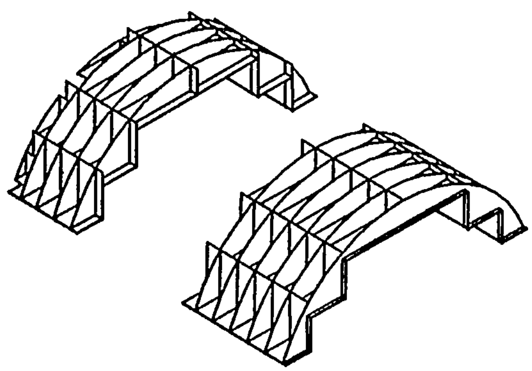
Integrating the production planners into the design process, and into the solids modeling community, began in contract design. Contract design spanned the time period of mid 1985 through early 1987. The first goal was a set of high-level decisions about the build strategy of the vessel. Fulfilling the program requirement for a modular construction building plan required identification of hullseams, deck breaks, and major structural tank assemblies, even as the parameters of the vessel were being finalized (Figure 4). The ability to make these decisions was facilitated by the planners' production experience, and by design images produced by the modeling system. The goal of the production team was to develop and document a build strategy that took maximum advantage of the assembly and outfitting of large structural elements prior to bringing those units to the ship proper. For this effort the computer system provided the structural planners with the ability to examine the structure, with the appropriate outfitting counterparts, and define large pre-outfitted hull, deck, and tank assemblies. Previously, this type of coordinated approach to planning both structure and outfitting was either difficult or impossible, due to the limitations of design materials. The solids modeling system's viewing features fostered a high level of confidence that the major elements of the construction plan, though aggressive, were attainable.

In addition to structural element definition, a similar effort was undertaken to define modules of large self-contained functional systems. The modules consisted of major components, piping, and cable generally located on common bedplates or platforms. Where the structural planning effort intended to streamline the erection sequence of the vessel, the effort to define "modules" was aimed at maximizing the installation, testing, and operation of the ship's functional systems away from the confines of the hull cylinders. While designers located major components and equipment within the hull, the planners and designers identified specific units of the geometry that were module candidates. The candidates were grouped together and documented in the model for the design community to see. The objective was to concentrate the arrangement of systems within the boundaries of modules to support common foundations, and off-hull system outfitting and testing (Figure 5).

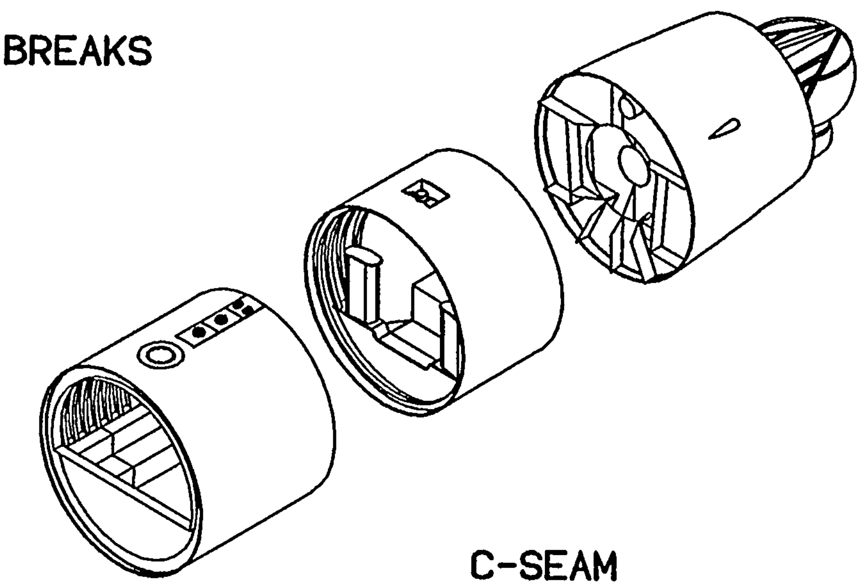
Integrating construction planning into the design



DECK BREAKS

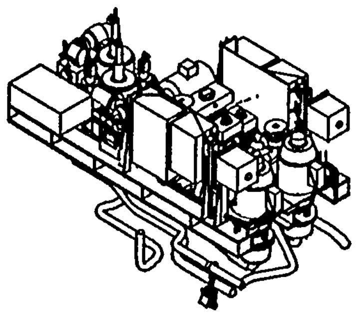


TANK
ASSEMBLIES

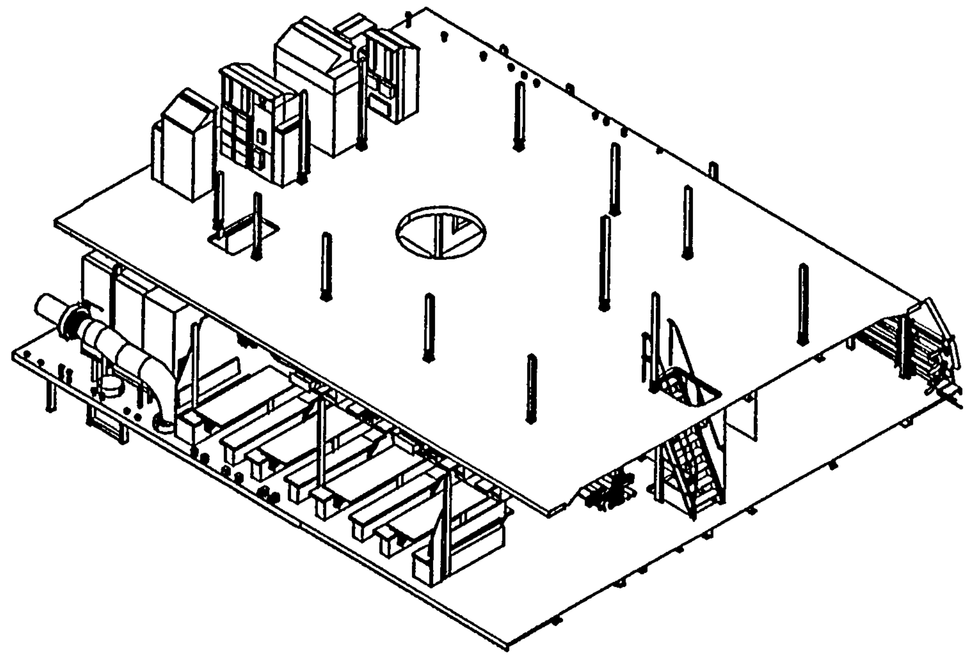


C-SEAM

FIGURE 4



BEDPLATE
MODULE



DECK MODULE

FIGURE 5

process resulted in the definition of the elements for an aggressive modular construction build strategy. Construction decisions such as circumferential seams and deck-breaks were recorded in the model to inform the design community, and to enhance producibility. The software's ability to incorporate and display planning decisions, and the overall construction strategy, reinforced the goal of a producible ship design. Performing this function in the early stages of a ship design, especially one as complex and as sequence critical as a nuclear-powered attack submarine, flushed out design production conflicts that are more costly to resolve at later stages of design or construction.

Detail Design

The relatively high-level decisions of contract design transitioned to fulfilling lead design yard responsibility on the detail design for SEAWOLF. One specification requirement of the detail design effort is the development of a detail construction plan. This plan consists of discreet work activities documented in a critical path management (CPM) network. The design data required to accomplish each of these modular construction activities are depicted on an SCD. Each SCD is a complete and comprehensive package of design data for the purposes of accomplishing fabrication, assembly, and installation of its respective modular construction activities (4). The CPM network documents the interrelations between the SCDs and establishes the construction sequence. As an aside, it also provides the schedule base-line to measure the performance of both the design agent and the builder(5). Due to specification requirements to issue construction-ready documents to the builder, the functional system configuration of the design is transformed into the units of modular construction depicted on SCDs.

SCDs are defined within the 3-D modeling system by construction planners on a piece-part basis. Each individual part in the model is examined by planning, and assigned to an SCD. This process occurs concurrently with design in order to have the maximum impact on the producibility of each part and its arrangement. The integration strategy for SCD development dictates that as the design for each compartment moves towards completion, the SCD boundaries are established. These boundaries are defined and documented by construction planners within the model. Essentially, this process is the development of a complete list of design parts to be contained on the SCD. This definition is performed based on specific criteria meant to enhance the constructibility of the design geometry. Examining the design geometry in its position within the modeled ship allows planners to visualize the installation of the final assembly of the particular product (Figure 6). In this application, the construction planners use the 3-D view features to analyze and eliminate loading interferences, to maximize favorable weld joint positions, and to generally prove the

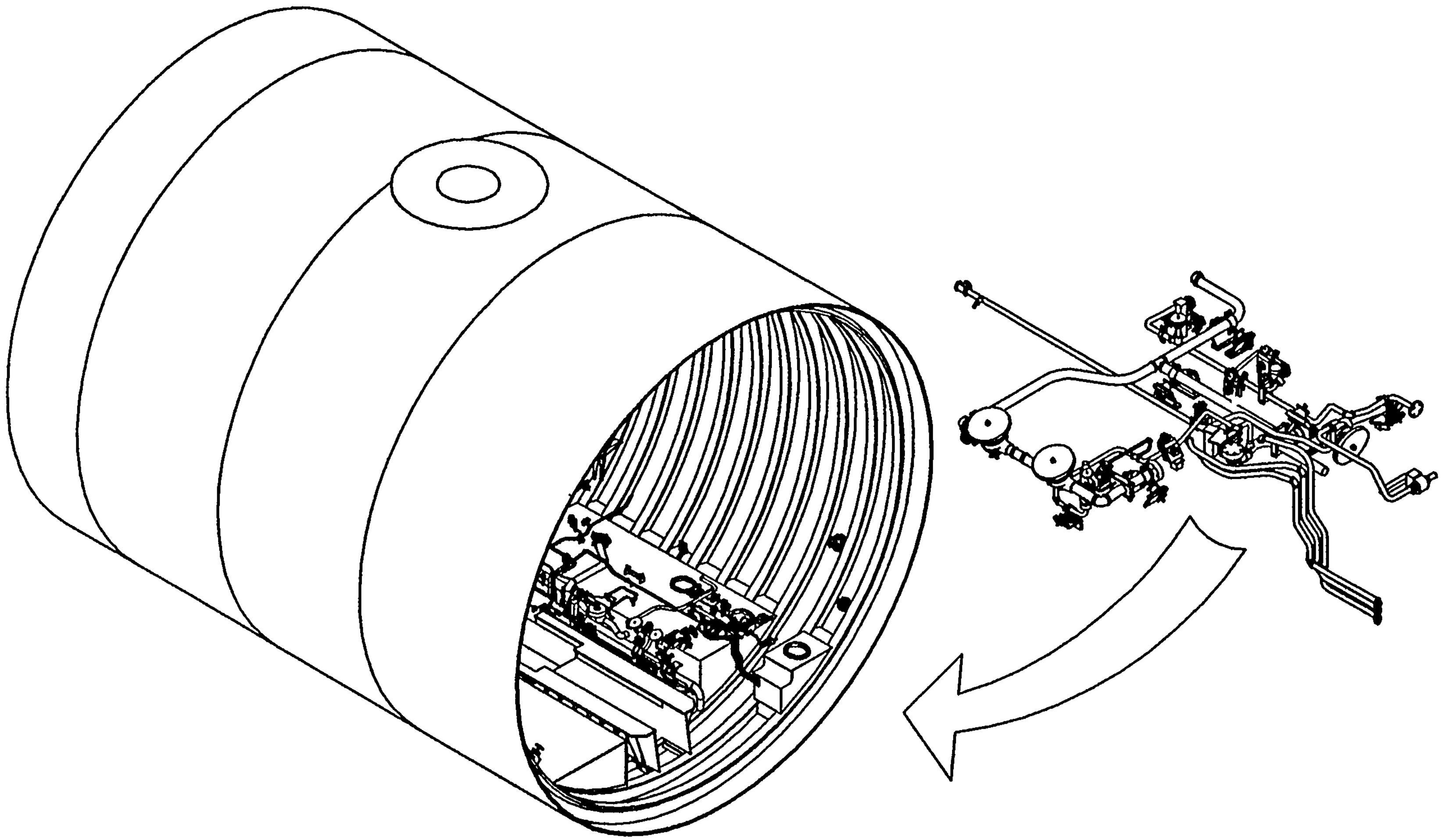


FIGURE 6

effectiveness of the design. SCD development often generates feedback to the design team that modifications are required to the geometry. The product of this initial planning phase is a complete list of parts for depiction on the SCD.

However, the SCD list does not satisfy all of the requirements for the drawing. The SCD must contain the fabrication and assembly data required to prepare the product for installation into the hull or module. Planning the manufacturing of pre-assemblies and assemblies for structural, piping, ventilation, and other outfitting products is critical to the effectiveness of the construction strategy. Modular construction strategies must maximize the assembly of the vessel's geometry outside the confines of the hull. In other words, the strategy must take advantage of assembly in shops and on platens prior to transferring those interim products to the ship proper. By viewing the previously defined SCD boundaries stored in the model, the planners can evaluate the most favorable assembly sequences for the parts. Evaluating the assembly sequence requires a thorough knowledge of accepted shop fabrication practices and standard facilities. The most producible part combinations are formed together and documented within the model to the most complete level of assembly possible (Figure 7). Developing the planning products in these two separate stages ensures a high level of producibility before committing the data to the drawing.

The product of the detail design planning process for SEAWOLF is a collection of product structures that document total content and optimum assembly/installation sequence for each SCD. Product structures are stored as a unique non-geometric part class within the model. The product structures are then electronically transmitted to the draftsman, whose job it is to develop the drawing with the content and relationships as documented by the construction planner. This process is accomplished without production of interim design materials such as internal blueprints. The development of the design, the contents of the construction drawings, and the CAD views that eventually become the drawings are derived from the model. The depth of integration of production and design is producing a rigorously evaluated modular construction strategy.

DESIGN PRODUCTS

Integrating production into design through the use of solids modeling software affects the design deliverables. The development of traditional design products such as drawings is changing significantly. New deliverables are being created, and some products are being curtailed or eliminated.

<u>Drawings</u>

A primary impact to design deliverables that solids modeling technology is fostering is the conversion of the drawings from a functional system configuration to a construction product configuration. 3-D modeling essentially made this transformation possible by

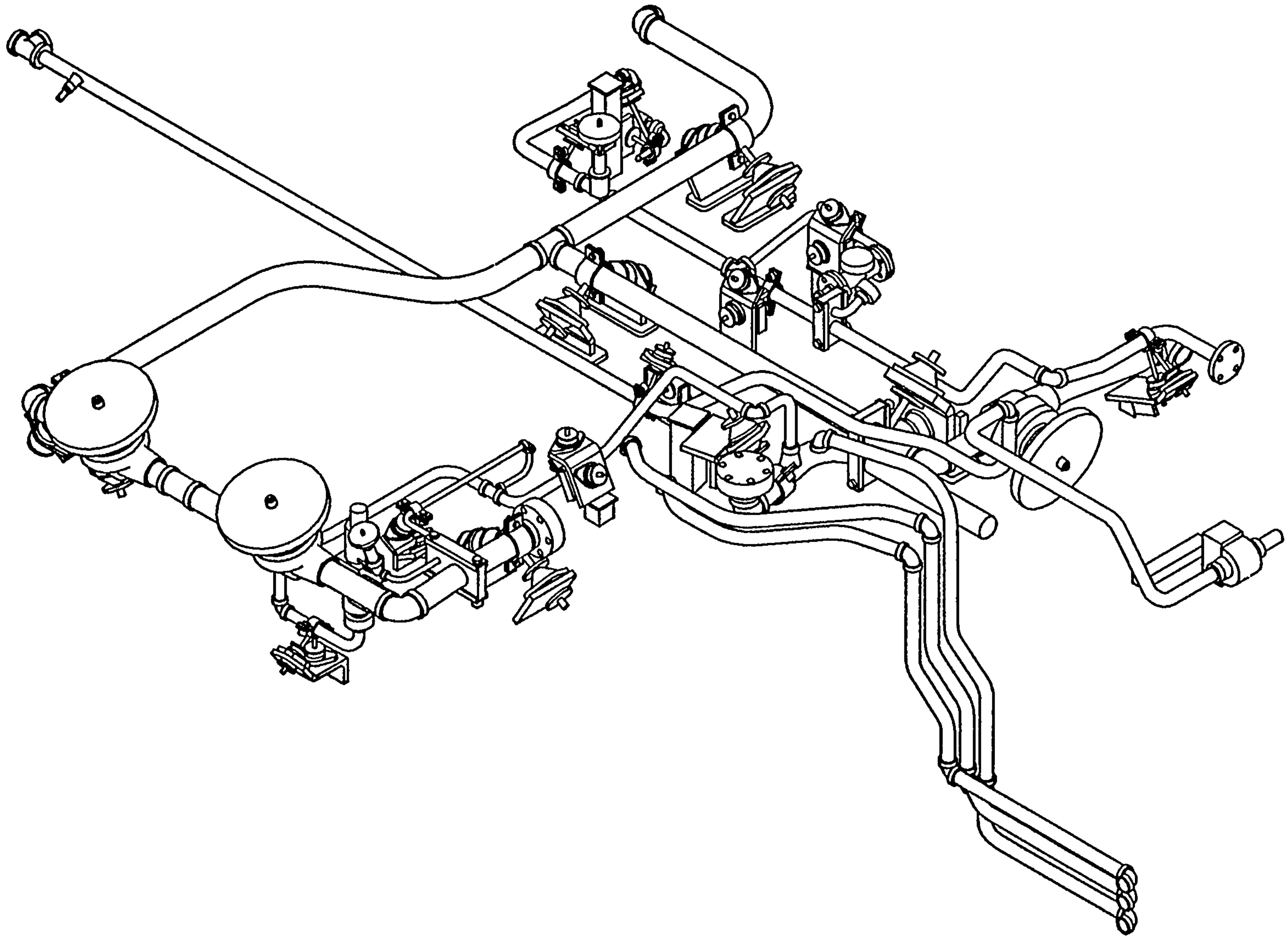


FIGURE 7

providing the planners with the ability to take apart the design and re-mold the data into the building blocks of the vessel, without the inefficiency of producing interim design documents. The SEAWOLF SCDs show that in addition to changing the form of the data, valuable information can be added to aid in construction. Typical design agent products do not provide all of the necessary dimensions and data needed for construction. Shipbuilders traditionally incur high value-added costs associated with design agent drawings. Traditional drawings require time-consuming interpretation by trades with less predictable results.

It is recognized on the SEAWOLF project that significant efficiencies could be gained by making the construction drawings sensitive to the trade's needs. The philosophy behind the SCD calls for limiting the included design data to the information needed for the corresponding construction activity. This information includes a bill-of-material that has defined and part-numbered material sources, a standard minimum tolerance for all operations, and improved accuracy of dimensioning and graphics. The accuracy of the design data is improving as a result of the use of CAD tools, that have a precision of several ten thousandths of an inch. Alterations are being made to the drawing graphics to compliment the change in drawing intent. Isometric views are added as the first view sheet of each SCD (Figure 8). This feature provides the trades with a way to visualize the extent of a particular job, thus reducing the amount of "start-up" time for each operation.

Another improvement in drawing graphics is matching the SCD drawing views to the actual position of the product in the corresponding construction stages. One example where this technique is particularly useful is the erection and outfitting of the platforms on SEAWOLF. The construction plan specifies the platform positions for each step in the process: it calls for the plate blanket and structure to be assembled, the underside of the deck to be outfitted, and then the inversion of the platform to outfit the top-side. The construction drawings that specify and correspond to each step of this sequence contain drawing views that match the dictated position of the platform (Figure 9). These views, as well as any other special views needed are specified by the construction planner, who developed the build strategy at the beginning of drawing development. The solids modeling system facilitates this construction-oriented approach to drawing graphics by allowing model viewing and drawing creation from any orientation. These views increase the capability of the design product, and ultimately the efficiency of the tradesman.

<u>Digital Design Data</u>

A new design product was introduced during the SEAWOLF project: digital design data. SEAWOLF design specifications dictate the development of standards for exchanging piping

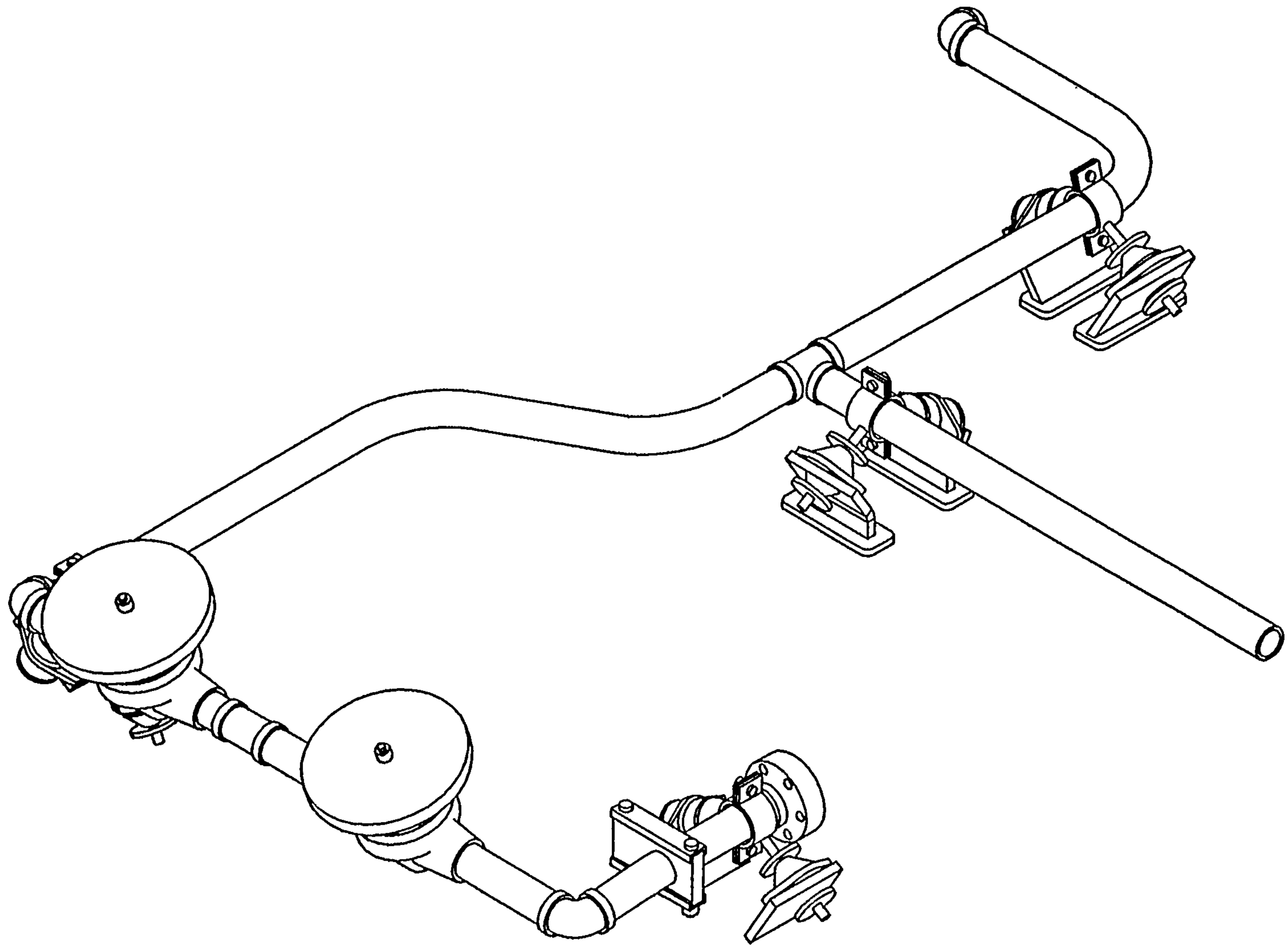


FIGURE 8

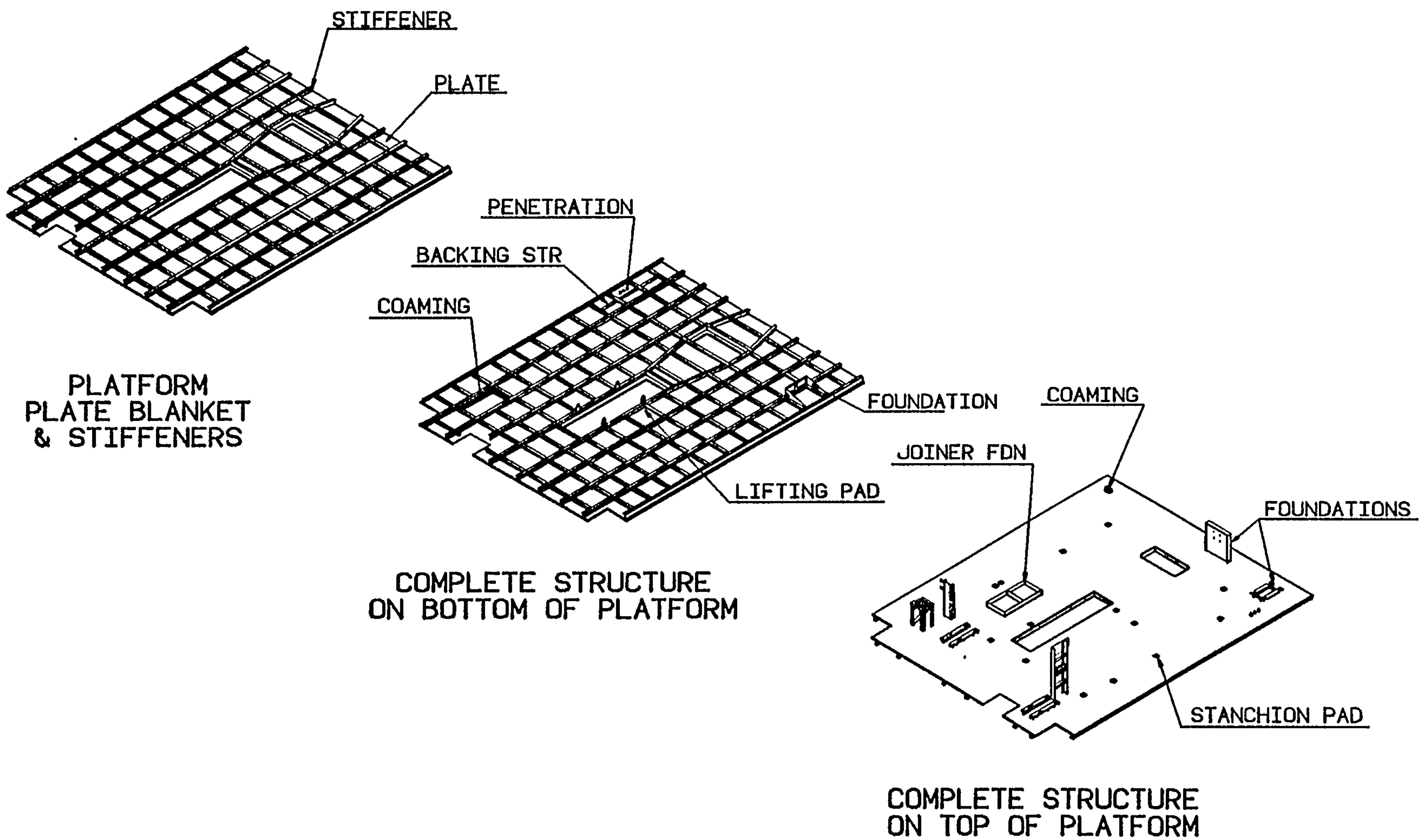

STIFFENER
PLATE
PLATFORM
PLATE BLANKET
& STIFFENERS
PENETRATION
BACKING STR
COAMING
FOUNDATION
LIFTING PAD
COMPLETE STRUCTURE
ON BOTTOM OF PLATFORM
COAMING
JOINER FDN
FOUNDATIONS
STANCHION PAD
COMPLETE STRUCTURE
ON TOP OF PLATFORM

FIGURE 9

digital product data between design agents and prospective builders. The exchange is accomplished by storing vital attributes about the design geometry on a magnetic tape in IGES format. The tapes are developed to be shipped and the stored design data retrieved on different machines. The portability of digital product data is critical to ensuring compatibility between different design agents and the builders. When using the 3-D product modeling system, the digital product data is a by-product of the modeling process; there is no extra effort required. The full potential of producing electronic data, in addition to or instead of paper drawings, has not been fully realized. Loading numerically controlled (NC) machines with electronic data extracted from the 3-D model could streamline the shipbuilding process. Perhaps the integration of computer aided manufacturing (CAM) will have the same impact on construction that CAD had on design.

Mock-Up

Potentially, one of the most visible modifications to the design product would be the elimination of a physical mock-up. Full scale mock-ups have been used as part of the submarine design process for many years. These mock-ups have become a primary tool in the validation process. The solids modeling system provides features for validating the model without constructing a physical mock-up. One of the major purposes of a mock-up is to facilitate the elimination of interferences. The interference analysis functions of the solids modeling system are proving to be almost perfectly effective in allocating space within the ship's arrangement, and interactively warning designers when there is an incursion. This feature has been refined to consider access and equipment cooling obstructions, up to and including the "swing" of locker doors and valve handles.

The second objective of the physical mock-up is slightly more difficult to satisfy using 3-D modeling. Physical mock-ups for submarine designs are used by the Navy's experienced submariners to evaluate operability, damage control, and maintenance attributes of the vessel's arrangement. The solids model representation does not always provide the same "hands-on," "view-from-station" objectives for personnel who must ensure mission capability and crew safety. However, recent improvements in view functions are winning over some skeptics. The advent of virtual reality technology may be the answer to addressing all of the concerns for operability. However, the U. S. Navy is satisfied with the SEAWOLF electronic model and is significantly curtailing the requirement for the forward-end physical mock-up. A detailed account of the SEAWOLF lead design yard's development and application of 3-D modeling as an elecltronic mock-up is contained in Tatum, et al's paper recently published (6).

FUTURE

Paperless Design

The final topic we will

discuss is the future applications of 3-D modeling and specifically the impacts on design products. Although not directly related to production planning integration, future enhancements to 3-D modeling could have significant impacts on design and manufacturing processes, and are therefore included in this paper. 3-D modeling has already had significant impacts on the design process and its products. Even though most agree that the capacity to generate, receive, and utilize electronic data exists, the essential products of the design effort are still paper drawings. The next frontier for design products is the elimination of most of the effort and cost associated with traditional drawing development and issue. The concept of paper-less design has many benefits for design agencies, but a few drawbacks for end-users of the design data. From a design agent's perspective, developing and generating purely electronic data eliminates reproduction costs and vault costs associated with storing paper drawings. Benefits for the end user obviously depend upon their ability to receive, manipulate, and distribute electronic data throughout their manufacturing processes. Unfortunately, end-user ability can vary from virtually no capacity to handle electronic data, to the ability to directly feed design data to NC machines. Many companies are discovering that paper is an expensive and cumbersome method of communicating design data. Using a CAD to CAM electronic link reduces local product costs, and reduces errors. Perhaps the most important objective of a paperless design is the speed at which products can move from a graphics terminal to a manufacturing shop. The most successful examples of this so far have been in the automobile industry, specifically Ford Motor Company. Ford is changing the concept of a drawing by utilizing data and minimizing the amount of dimensioning and other traditional design data contained in the CAD model (7).

A further innovation would provide an electronic copy of the solids model representation of a design to shipbuilders. In addition to eliminating the time and expense of drawing production for the design agent, this concept also has potential benefits for the builders. Chief among these benefits is the ability to customize the extraction of manufacturing data from the product model. Selecting manufacturing data by attributes such as material or other common traits allows tighter control of shop work loads, and greater efficiency through batch manufacturing. The design data are in a format that is conducive to generation of NC data, but can also be used to generate paper drawings for the production of assembly/installation sketches, and for generating design data to give to subcontractors. The extraction of the 453,000 parts from the SEAWOLF database could be accomplished with today's technology. However, there are significant issues to be addressed regarding an industry standard to ensure compatibility between companies for the elements of such data. A joint industry-government

committee is currently addressing such issues and expects to have a usable product by late 1994. Overall, there is a significant amount of inertia in the design/manufacturing industry that will have to be overcome before exchange of entire "models" becomes a reality.

Virtual Reality

Another consideration for future development is the emerging technology called virtual reality, or cyberspace. Research is currently underway for several forms of virtual reality. The category of partial immersion appears to be the most likely candidate for use in the shipbuilding industry. Partial immersion equipment usually consists of a helmet and gloves. A virtual reality helmet uses micro-screen technology to display stereoscopic visual images in front of a user's eyes. These images are generated in such a manner that a user "feelsl" like he or she is inside the model. The computer that generates the visual images updates the displays to accurately portray what the user sees, accounting for head motion and "virtual movement" throughout the model. A virtual reality glove could be integrated into the system to sense the hand motions of the user. The glove would allow the user to interact with the objects in the model. Potentially, the glove could allow the user to touch, move, change, react to, or cause reactions in objects.

With the technology available today, images of complex models cannot be generated and displayed quickly enough to provide a reasonable simulation. This results in jerky transitions between views of even relatively simple models. Rapid advances in microprocessor technology may soon make available computer systems with the power required to implement such a system. Until that time the challenge of providing images which realistically capture real-time motion in a complex model remains.

Assuming that performance improves and the cost is reasonable, virtual reality could be a useful tool in production planning. The most obvious benefit is increased visualization. The VIVID ® system already allows single views from the vantage point of a human in the model. These views can be shown in sequence to create an illusion of walking through the model. Virtual reality would take this capability a step further and allow a user to determine path and view as they are walking through the model. The image would appear to be three dimensional. Currently,, production planning rarely uses the human vantage point feature, due to the set up time needed for each view. Instead, production planning manipulates views which show an outside the model representation, to evaluate construction processes. Operating in a virtual reality environment would be more interactive and intuitive, since the views are not pre-determined, are generated in real-time, and are from a human vantage point. Evaluating component loading sequence and loading paths would be as simple as "picking-up" the component(s) and moving it around the model.

The technology will have an impact on how aggressively and how detailed planning organizations are willing to direct production. Current technology limitations produce an uncertainty between planning and production. Using virtual reality technology production planners could simulate complex processes and decrease the uncertainty. Application of this technology would also facilitate greater certainty in predicting each step in an installation of a piece-part or maintenance of a component. For many situations this level of detail is not necessary. However, there are some processes where every detail and every step is practiced and monitored. Operations such as overhauling nuclear components or repairing orbiting satellites could be practiced by using the virtual reality simulation with less expense and effort than building a physical replica. Development and use of such technology will have far reaching effects on planning, and therefore management of complex processes.

SUMMARY

The advent of 3-D modeling technology has been the most significant contributor to the success of integrating production and design. The LDY's decision to design the forward end of SEAWOLF completely within the product modeling system demonstrates that a reformation of basic design agent deliverables and the inclusion of manufacturing intensive data in the design is attainable. Using the 3-D modeling system for SEAWOLF also facilitates the evolution of design deliverables from strictly paper and physical products to electronic products, saving both cost and schedule. There remain, however, many more cost and efficiency improving innovations that can be derived from and used in conjunction with 3-D modeling. Future submarine and surface ship designs will certainly take advantage of model technology and production planning integration. The application of this concept will expand as industry focuses on improving quality and driving down costs in order to stay competitive in today's market.

REFERENCES

1. J. R. Lindgren, Jr., W. A. Solitario, A. P. Moore and M. A. Streif, "CAD/CAM Gores to Sea: the SA'AR 5 Design and Construction," *Naval Engineers Journal,* May 1992.

2. CMDR W. R. Schmidt, J. R. Vander Schaaf, R. V. Shields III, "Modeling and Transfer of Product Model Digital Data for the DDG 51 Class Destroyer Program," NSRP Ship Production Symposium, August 21-24, 1990.

3. "Final Assembly of 777 Nears," *Aviation Week and Space Technology,* October 12, 1992, pp. 48-50.

4. S. E. Bevins, C. F. Clemens Jr, D. E. King, T. H. Koger Jr., and R. R. Pollock, "SEAWOLF Design for Modular Construction," *Marine Technology,* Vol *29 No. 4,* October 1992, pp. 199-225.

5. J. P. Chappell, “The Application of Critical Path Methodology to the Management of Ship Design Programs,” *Marine Technology,* Vol *28 No. 3,* May 1991, pp. 113-128.

6. *S.* A. Tatum, J. C. Byrum, and P. W. Rourke, “Design Validation Using Computer Models in lieu of Full-Scale Mock-ups,” SNAME, *Hampton Roads Section,* January 28, 1993.

7. *“CAD* as Master,” *Computer Aided Design Report,* Vol. *13 No. 1,* January 1993, PP. 1-60

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Design/Production Integration

W. W. VanDevender (V) and A. S. Holland (V)-Ingalls Shipbuilding

ABSTRACT

The multiple challenges posed by ever-increasing ship sizes, technical complexity, skyrocketing material and construction costs, plus several recently introduced design requirements - such as double hulls and extensive waste treatment systems - have combined to create an increasingly involved and complicated shipbuilding environment. This paper addresses steps taken to increase design and construction effectiveness through use of a shared three dimensional (3-D) database. An improved ability to successfully compete in the highly competitive international shipbuilding market is demonstrated.

INTRODUCTION

The United States shipbuilding industry is facing major problems from intensely competitive, and often government-subsidized shipyards in both Europe and the Far East. The outlook at this time is not promising, and the only hope of becoming competitive lies in streamlining the ship design and manufacturing processes, strictly controlling production costs and overhead, and providing a top quality product that will please the customer and induce them, and hopefully others, to return to the United States with additionaal order in the future.

In order to survive as a viable industry, shipbuilders must not only rely on the latest technology, but also must employ every means available to simultaneously decrease cost and increase productivity. To achieve this, every task and step in the design and manufacturing process must be thoroughly evaluated to ensure maximum efficiency. Personnel who in the past have specialized within one narrow field must increase their versatility and learn to apply their particular knowledge over a broader spectrum than before.

At Ingalls Shipbuilding the concept of concurrent engineering with a comprehensive 3-D Computer Aided Design (CAD) database is applied to achieve a more streamlined and productive design for manufacturing. This method has proven capable of

eliminating many of the major and minor problems that tend to occur downstream in the material, planning, and operations stages of the ship design and manufacturing processes.

This paper provides a brief review of the subject of concurrent engineering and design/operations integration and outlines the positive aspects of implementing its principles.

THE PRINCIPLES OF INTEGRATING DESIGN AND PRODUCTION PERSONNEL

Until recently a ship design was created by various disciplines working separately from the start of a project; only upon completion of individual efforts were the results integrated into one cohesive design package. However, this method was inefficient and uneconomical since it invariably resulted in extensive overlaps and duplications of effort, as well as conflicts and interferences throughout the design. Accordingly, much time and cost had to be expended in backtracking and correcting already finalized series of drawings, instructions, and work packages.

Implementation of the concept of concurrent engineering has resolved many of these inefficiencies. This involves the use of integrated teams of representatives from all disciplines and crafts working in close coordination from the initial design through completion of construction. The second reason for the success of the concurrent engineering concept is the extensive use of a three-dimensional CAD system which, among many other capabilities, enables engineers, planners, and craft supervisors to observe three-dimensional images of spaces and equipment arrangements as they actually would appear on a ship. This is a tremendous advantage over earlier methods, where the individuals involved had to rely on two-dimensional design drawings to define arrangements and installation procedures, and then mentally convert these to three-dimensions.

An additional benefit of using a CAD system is that its output can be used to create data for use in Computer Aided Manufacturing (CAM). This is accomplished through Direct Numerical Control (DNC) data - directly generated from 3-D CAD database into a computer, which then issues instructions to shop machinery for plasma arc cutting of steel and aluminum plate, pipe bending and cutting, and other fabrication functions.

Implementation of this concept has resulted in a design product with far less need for change, since all major issues and potential problems have been identified, resolved, and incorporated from the start of the design process. The overall result of this teamwork has been ship designs created with far less duplication of effort, and improved producibility, and a less expensive end product that is delivered in the shortest possible period of time.

The transition to the concurrent engineering concept and design/operation integration was initiated with an evaluation of each shipyard organization’s structure, arrangement, and operating principles. For example, the engineering organization had always been divided into two distinct groups: de-

sign engineering and field engineering. Design engineering was responsible for completion of all initial design tasks and then, upon start of production, would transfer most of its responsibilities to field engineering. Although the two groups communicated well, it was evident that neither was fully capable of resolving all problems occurring during the various stages of design and production.

Accordingly, it was decided to form teams of key personnel from all departments into coherent design\operations teams for each design discipline. One group each was formed from naval architecture, marine engineering, and combat systems/electrical. Each group included a principal engineer in charge of several other engineers, a principal designed and a number of CAD designers, senior planners, weight control specialists, material specialist, and operations supervisors.

Each team was placed under the direction of project coordinator, answerable to the director of engineering, (Fig. 1) who was responsible for scheduling, budgets, and liaison between the three design disciplines and all affected organizations.

Since engineering and design personnel could not be expected be familiar with all of the most recent manufacturing processes employed at the various craft levels, it was decided that craft supervisors should

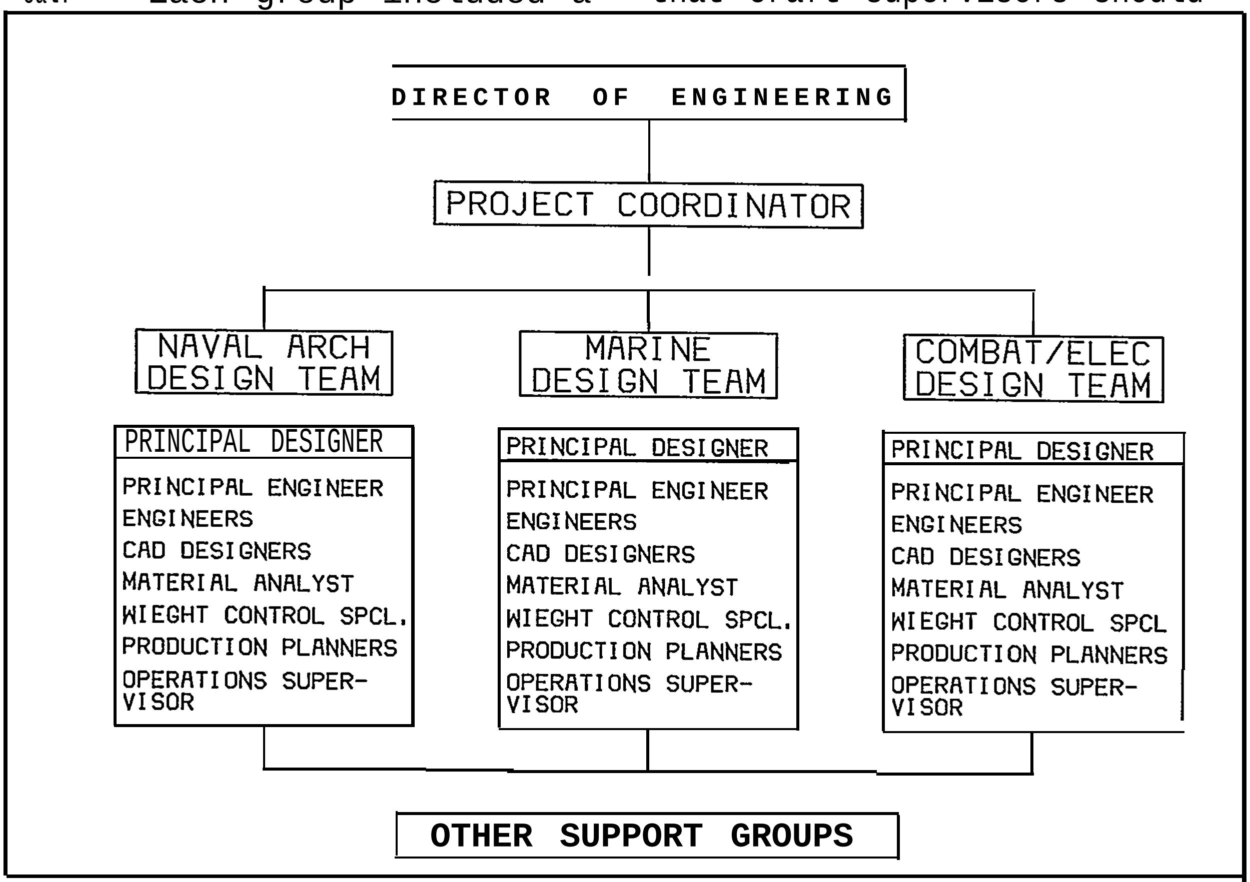

Figure I-Typical Organization Chart

be integrated into the engineering organization to provide information and to help develop a better understanding of problems that might occur at construction sites. Thus, by having experienced craft supervisors work with the design team, potential manufacturing problems could be corrected prior to release of drawings and start of construction. This saved much valuable time that might otherwise have to be wasted in taking out erroneously installed equipment or systems.

Subsequently, it was found that one of the main benefits of integrating operations personnel with the design team was the valuable practical information these experienced supervisors were able to pass to the designers. They inspected congested areas on the ship to determine the best possible means of production.

By using the Project Review Terminal (PRT) they could visualize all components, and make valuable suggestions to the design team for enhancement of the basic design. Operations personnel also assisted in the selection of candidates for machinery packages, selected HVAC and pipe spools for fabrication, and identified assembly beaks in spools for distributive systems.

By following the design from its inception, the craft supervisors became thoroughly familiar with all spaces, and after a year or more of constant observation of the design, they were able to provide expert guidance and assistance to crafts personnel on any problem anywhere in the ship. This greatly increased production efficiency and, in general, resulted in an improved product which could proudly meet the production motto of “HEAD OF SCHEDULE AND UNDER BUDGET!”

DESIGN TEAM RESPONSIBILITIES

With these teams of highly qualified personnel in place the shipyard was ready to accept the challenge of constructing the first totally CAD-designed and CAM-produced ship using concurrent engineering principles. The following are brief descriptions of the responsibilities placed on the individual team members.

Principal Engineer

The principal engineers were responsible for ship systems and technical areas, and supervised a group of other engineers who performed analyses and developed systems within each of the technical areas. They also functioned as the primary customer contacts in regards to technical matters.

In addition, the principal engineers monitored each design task, held design reviews to resolve conflicts, and interfaced with all disciplines. Not only did they act as experts within their own field of endeavor, but they were required to familiarize themselves with the overall design to a degree where they were able to provide objective and positive input to areas not normally under their cognizance.

Engineer

Under the general guidance and leadership of the principal engineers, and based on the ship’s specifications and system

design requirements, the team engineer developed one-line diagrammatic drawings (diagrams), to include the latest vendor information, stress analyses, and systems calculations. Next, the information was compiled and loaded into the CAD database under the guidance of the engineer, and they regularly updated to ensure that each designer would have the most recent information available for the design effort.

Other responsibilities included interfacing with vendors regarding major equipment, preparations of advance bills of material for long lead items to support production schedules, participation in the resolution of design problems, and acting as a source of on-site information for the CAD designer.

Principal Designer

Each designer organization appointed one lead designer to coordinate the initial design for their respective discipline. The principal designers from all disciplines were co-located in the CAD area, and began the initial design using all available information to generate one-line composite drawings for loading into the CAD database.

The fact that personnel from all organizations were located within the same room or area provided the vital communications link required to incorporate all valid information into the design.

Whereas the principal engineers were responsible for ship systems and technical areas, the principal designers controlled development of the design within each design zone. They interfaced on a continuing basis with the principal engineers, CAD designers, material analysts, weight control specialists, operations personnel, and production planning personnel to ensure that valid comments from all sources were incorporated into the design. In addition, they chaired design reviews for their respective discipline, or for the design zone under their responsibility.

The principal designer worked directly with the assigned operations\craft personnel from the start of the project. Each component was scrutinized, placed on the composite, and loaded into the CAD database to support fabrication and installation. Various components were grouped to support machinery packaging. These areas of the machinery spaces were designed for fabrication in the machinery package shop, and subsequent landing on the ship. With the assistance of production personnel, these packages were structurally designed to support equipment, distributive systems, outfitting, and testing.

Following completion of the design, the principal designers moved their work stations to the production area where they coordinated with operations personnel and field engineers to resolve production conflicts. Due to their extensive knowledge of the overall project they were usually able to solve production problems with minimum delays or disruption to other work in progress.

CAD Designer

The CAD designer would load the 3-D CAD database using diagrams, one-line composite

ketches, contract guidance drawings, and preliminary structural disciplines to develop arrangements and distributive systems. After completion of the zone structural models, major equipment was created and arranged. These included maintenance envelopes for access control, equipment removal, shock and vibration, and headroom. A priority routing system was then used to design HVAC, wireways, and large piping systems. The last items to be generated were smaller pieces of electronic equipment, local wireways, outfitting, furnishings, and small pipe.

The CAD designer interfaced with all affected organizations and personnel during this process. The design of distributive systems was monitored on a continuing basis by the principal engineer, principal designer, and personnel from material, operations, and planning. This was the phase of the design in which all responsible parties would correct potential problems that might occur downstream.

Using a CAD database provided the opportunity to interference check all systems and components as they were placed in the CAD model. All observed problems were logged and tracked by the CAD designer, and models were not released for drawing extraction until all interferences had been cleared.

Following completion of the design, the CAD operator was responsible for extracting the design drawings from the database. Such extractions were created to support the needs of the planners and craftsmen. In lieu of conventional types of drawings, many of the distributive systems drawings were created to support downhand welding. Operations and planning personnel defined which ares were to be developed using this method; this was a valuable asset to operations personnel, as it provided a clear perspective of components being installed.

Upon start of construction, lead CAD designers were relocated to the production area, along with their CAD work station, to coordinate with and support operations personnel with on-site resolution of production problems. This eliminated the functions normally performed by field engineers, since the operator identified the problems on the ship, corrected the CAD database, updated the DNC, and revised the applicable drawing. Being able to work on site with operations personnel who were familiar with the CAD design tools greatly expedited processing of each change.

Material Analyst

The materials entered into the CAD database were controlled and monitored by the material analyst, who decided what would actually be procured for the construction project.

All materials were programmatically sourced by the material analyst from each CAD model, and checked to verify that all components were identified for purchasing. Checks were also made to identify non-standard items with long lead times.

Suggestions would occasionally be made by the analyst to the principal engineer to substitute one material for

another, either due to a large in-yard inventory, or to save in cost.

Weight Control Specialist

Since all ships have stringent weight restrictions, it was the responsibility of the weight control specialist to monitor all components placed in the CAD models. As the design was being generated, preliminary bills of material were extracted for the purpose of evaluating the weights of the materials used. If lighter-weight substitutions could be found for components, and still met the required specifications, then the weight control specialist requested the design team to make the substitution.

Also, in order to maintain a load balance of the components placed on the ship, it was the weight control specialist's responsibility to calculate all loads and establish centers of gravity. If it was necessary to relocate components, specialist would identify these to the team for relocation action.

Production Planning and Billing Personnel

These specialists, normally located in the production area, were relocated with CAD designers to plan and stage the fabrication and installation of each component. The information entered into the CAD design models included all applicable location, planning, and billing data. As the design was firmed up in a particular zone or area of the ship, the models were moved to the planners. Production planners, in conjunction with operations personnel, evaluated each component in each model. Pipe and HVAC spools were identified at that time, and items assigned to specific bills to be fabricated, installed in the pre-outfit stage, and subsequently in the final outfitting stage.

Operations Supervisor

It was the operations supervisor's responsibility to monitor the entire design process as the representative of manufacturing. They would provide input in any area to increase the productivity, select candidates for machinery packaging, select HVAC and pipe spools for fabrication, and identify assembly breaks in spools for distributive systems. Because they were able to see the design as it progressed, the operations supervisors became very familiar with each space. After a year of reviewing the plans they knew exactly what their job was and how to do it.

DESIGN DEVELOPMENT PROCESS

The detail design effort was divided into three phases: functional design, transition design and working instructions. (Table I).

The functional design involved preparation of basic engineering calculations, equipment selection, and preparation of schematic diagrams for pipe, vent, and electrical systems. Items such as longitudinal strength, superstructure air blast resistance, and other basic structural analyses were also completed in this phase. In addition, key space arrangements were established, and weight budgets allocated to various systems and equipments.

STAGE 1	STAGE 2	STAGE 3
FUNCTIONAL DESIGN	TRANSITION DESIGN	WORKING INSTRUCTIONS
SPECIFICATIONS REVIEW	FINAL MAIN STRUCTURE MODELS	DEVELOP STRUCTURAL FABRICATION DRAWINGS
SCANTLING CALCULATIONS & PREPERATIONS	DEVELOP CONNECTING STRUCTURE & FOUNDATIONS	DEVELOP STRUCTURAL INSTALLATION DRAWINGS
LINE FARING	DEVELOP FINAL EQPT. ARRANGEMENTS	DEVELOP FINAL ARRGT. DRAWINGS
C & A DEVELOPMENT	DELVLOP DISTRIBUTIVE SYSTEM ROUTINGS	DEVELOP FINAL MACHINERY PACKAGES
KEY SPACE ARRANGEMENT	FINALIZE MACHINERY PACKAGES	GENERATE DNC DATA
SYSTEM CALCULATIONS	PENETRATIONS	DEVELOP FINAL SHOP FABRICATION SKETCHES
WIEGHT REVIEWS	LOAD DNC DATA	DEVELOP INSTALLATION DRAWINGS
PRELIMINARY DISTRIBUTIVE SYSTEM ROUTING	LOAD PLANNING & BILLING DATA	
WELDING PLANS	DEFINE FABRACATION REQUIRMENTS	
STANDARD DETAIL DEVELOPMENT	DEFINE INSTALLATION REQUIRMENTS	
MACHINERY PACKAGE SELECTION	FINAL INTERFERENCE CHECKING	
ADVANCE BILL OF MATERIALS	FINALIZE BILL OF MATERIALS	
DEFINE ASSEMBLY BREAKDOWNS	INCORPORATE ALL OUTSTANDING COMMENTS	
CREATE INTERFERENCE CHECKING PROJECTS		

Table I -Zone Breakdown Table

The zone design phase involved creation of a three-dimensional CAD product model for each design zone. The product model showed all elements of the ship: including structure, equipment arrangements, piping and ventilation systems and hangers, wireways, waveguides, and foundations. The product model was checked for interferences and compliance with all specifications prior to start of the production design phase.

The production design phase involved determining of the design geometry. The purpose was to prepare a design that would be in the most usable format possible for the craftsmen. Work packages for shop fabrication and field installation were also prepared in this phase. Material allocation was an important part of this phase. Raw material was allocated toshops with fabrication packages, and completed shop sub-assemblies allocated to pre-outfitting and outfitting packages.

During the above phases, information was programmatically associated to each component in the CAD models by planners experienced in operation of the CAD system. This knowledge gave planning and operations personnel a valuable insight into the actual design, which permitted them to communicate and interface far more effectively with engineers and CAD designers than under the conventional methods used in earlier projects.

PROJECT REVIEW

As the results of, the design effort began to materialize, a Project Review Terminal (PRT) was put into use. This terminal was a work station capable of providing true 3-D perspectives of each design zone (Fig. 2) as it was generated in the CAD database. The colored

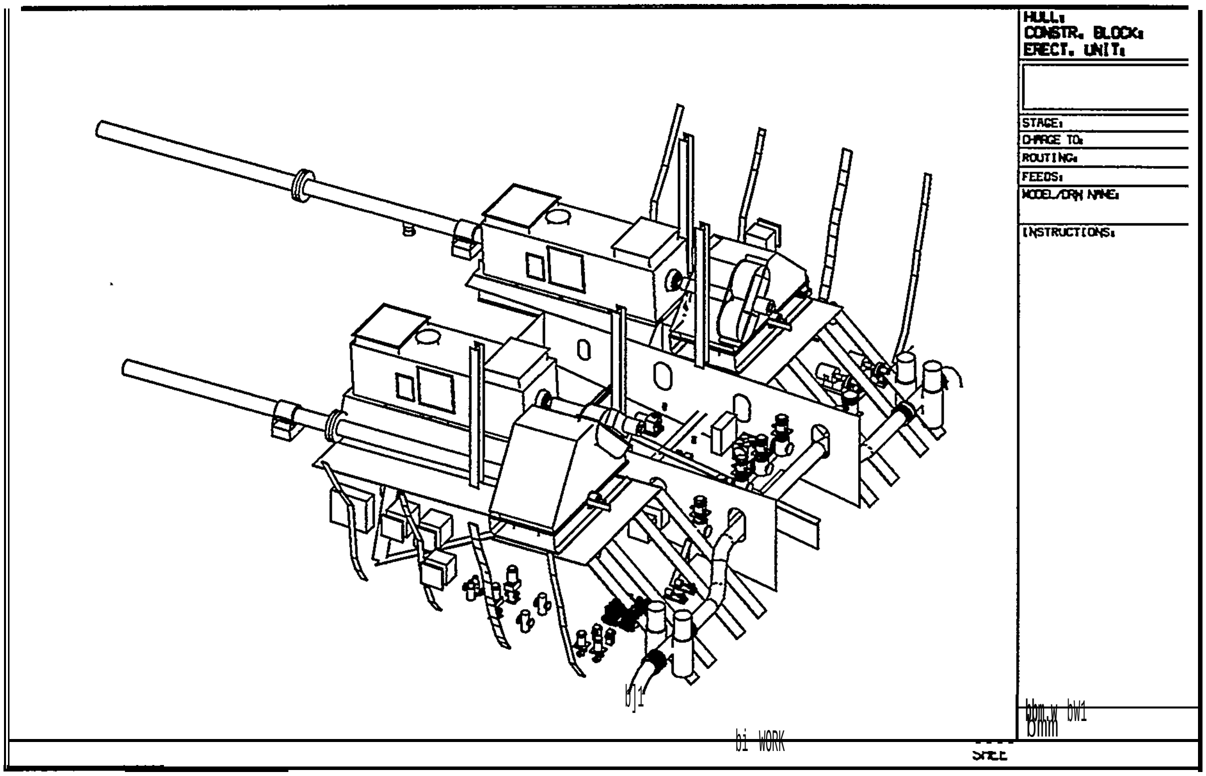

Figure 2 - Typical PRT Image

and shaded images, which may be available up to two years prior to construction, showed the model as it would appear to the craftsman working on the ship. Also, it might be viewed from any angle, and could be inverted from its design orientation to show how it would appear during various stages of construction. A built-in "blanking feature" allowed different systems or items of equipment within a compartment or space to be either shown or blanked out at will.

One of the benefits of the PRT was that, for example, the supervisor in charge of piping systems in a machinery space would know exactly how the space would look and be equipped prior to installation of the first piece of pipe. Also, in view of a supervisor's experience with earlier construction projects, they might, based on the PRT presentation, be able to identify potential installation prob lems or conflicts and arrange to have these corrected prior to start of construction. They might also be able to assist planning personnel with start of construction, and with information regarding which portions of each system should be installed during what phase. These "lock-out areas" - as they are called - could be clearly defined on the PRT, and appropriate action could be taken to avoid expensive and time-consuming rip-out of components installed in the wrong sequence.

At this stage, occasional minor items that might have been overlooked by the designers in the initial phases were identified by operations and planning personnel. These people acted as "checks and balances" throughout the design phase, thereby contributing to the creation of a superior product, with resulting improvements in production, time and cost.

As the design was finalized, all applicable drawings were extracted by the production planners and plotted for distribution to the crafts.

CAD/CAM INTERACTION

An additional timesaving benefit of using the CAD/CAM system was that the CAD equipment was capable of producing magnetic tapes containing machine instructions which would direct the operation of shop manufacturing machinery. This was accomplished through the use of Direct Numerical Control (DNC) data, which was generated by downloading numerical data into a computer as a manufacturing aid for pipe bending, plasma arc cutting of steel and aluminum, and other functions. This process was normally performed subsequent to completion of the design process; however, with the integrated CAD database offsets would directly download!

For example, instructions regarding where to create a break in a pipe or HVAC spool were fed into the CAD database by operations and planning personnel as part of the design. This information, in turn, fed a computer program which analyzed each spool and its contents and automatically generated DNC data, which then was downloaded to operate the shop machinery bending or cutting the pipe. These instructions were direct extracts from the CAD models. There was no human intervention and, thus, if the model was correct, the DNC data would be correct, and increased productivity was achieved.

ADVANTAGES AND BENEFITS OF CAD/CAM

Some of the notable benefits derived from use of the CAD\CAM system in conjunction with the concurrent engineering concept were as follows.

Improved Design Team Access

Design data entered in the CAD system could readily be called up on the terminals for review by team members. Manual designs, on the other hand, tend to remain hidden in the numerous partially completed drawings and sketches that are in evidence during the design phase.

Increased Productivity

Much redundant work was eliminated by relying on model libraries for such items as background arrangements, standard details, and equipment models.

Development of Production Work Packages

As soon as a CAD model was developed and interference checked, it could be used for extraction of construction drawings. Such work packages contained only the information and material needed to support a particular work operation. (Fig. 3). This freed craftsman from having to extract the required work information from large system-oriented drawings. Separate packages were prepared for assembly pre-outfitting, shop fabrication, and final outfit work.

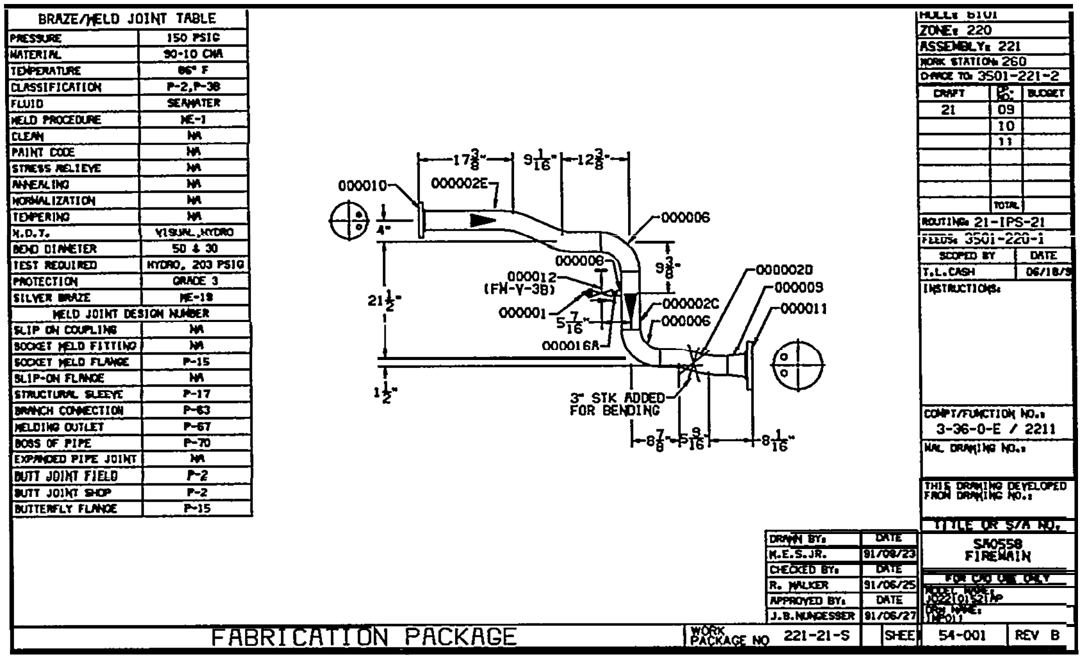

Figure 3 - Typical Fabrication Sketch

Improved Interference Checking

Three-dimensional CAD systems could control modeled objects at all points in space, and detect interferences at all levels. Two-dimensional techniques only show objects in selected planes, and experience subjective judgement. Therefore, a 3-D had to be applied in the final identification of interferences.

Customer Visibility

By using project review software, CAD models could be exposed to present the developing design to the customer. This technique might also be applied for design reviews and in the resolution of technical problems.

Computer Aided Manufacturing

CAD product models were used to prepare databases which, in turn, provided instructions to shop machinery for cutting steel or aluminum palates, fabricating sheetmetal, and bending and cutting pipe.

CONCLUSIONS

As a result of the decline in defense spending following the conclusion of the Cold War, the shipbuilding industry can no longer rely on defense contracts to maintain economical stability in the shipbuilding industry. Accordingly, the industry’s attention and efforts must now be directed towards the worldwide commercial market. However, unless the industry can remain competitive with the large, modern, highly effective, and in many cases government-subsidized shipyards that exist in both Europe and the Far East, its very existence is in jeopardy.

In order to survive in the international shipbuilding market, it is imperative that the industry continually evaluate and update every facet of the ship design and manufacturing processes, as well as delete all unnecessary tasks and positions.

One of the benefits of integrating craft supervisors into the design team was the

valuable practical information these experienced production supervisors were able to convey to the designers. This eliminated many potential problems during the production stage.

Craft supervisors working with the design team from its inception became thoroughly familiar with the design, and therefore were able to provide expert guidance to craft personnel on any problem anywhere in the ship. This resulted in increased production efficiency.

Application of the concept of concurrent engineering has proven to be a valuable asset. Some shipyards may find, in conjunction with the method and by experimentation, that a mix of conventional and computerized methods are more effective in their particular endeavors than strictly one or the other.

The overall conclusion is that application of the design/operation integration concept can drastically reduce the number of problems normally encountered during the ship construction. As a result, production will increase and the goal of “AHEAD OF SCHEDULE AND UNDER BUDGET” will be achieved. The design/operation integration concept is a valuable and positive approach to the continued survival of the United States shipbuilding industry.

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1993 Ship Production Symposium
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Integrated Ship Design and Its Role in Enhancing Ship Production

Jonathan M. Ross **(M)-Ross-McNatt Architects**

ABSTRACT

This paper focuses on an important trend that is increasing shipbuilding productivity: integrating the computer-aided ship design process The ship design process is increasingly being performed with the help of computer programs, either individual programs that address single aspects of the design or integrated programs comprised of modules that address a range of ship design aspects. In the case of integrated computer programs, the ship design process is enhanced through individual program modules sharing their results with each other, preferably from a common database. Modem integrated ship design programs not only improve the efficiency of ship design, they also improve the efficiency and ease of ship production from lofting and numerical cutting to providing workshop drawings and production information.

NOMENCLATURE

CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAL	Computer Aided Lofting
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
DXF	Data exchange Format (proprietary to Autodesk Inc.)
ESPRIT	European Strategic Program for Research and Development in Information Technology
IGES	initial Graphics Exchange Specification
NC	Numerical Control
PC	Personal Computer
STEP	Standard for the Exchange of Product data
VLCC	Very Large Crude Carrier

INTRODUCTION

The integrated ship design program is a compelling concept and one whose time has come. It aims to digitize the traditional ship design 2-D drawings, bills of materials and schedules carry out complex design calculations; and, perhaps most importantly, advance the ship design process into the multi-user environment and provide the designer and the production shipyard with a full-ship, 3-D database. The advantages of an integrated ship design program include decreased design hours, reduced lead time, increased productivity, early detection of interferences, ease in making changes, a drastic reduction of information errors, and the availability of production-oriented data. The purpose of this paper is to introduce examples of integrated ship design programs, show how those programs achieve their high degree of integration% and describe how integrated ship design programs enhance ship production.

EXAMPLES OF INTEGRATED SHIP DESIGN PROGRAMS

Eight integrated ship design programs are presented in the paragraphs that follow HULLTECH, AutoSHIP System, FORAN, HICADEC, lMSA, TRIBON, NAPA and NAVSEA CAD-2. They area representative sample of today's state-of-the-art integrated ship design programs. Information on the programs was obtained from interviews, sales literature and correspondence with the organizations that have developed the programs. The programs, or at least the modules from which the programs are comprised, have been developed over a period of years and, without exception, are still being improved. Different programs focus on different phases of the design/production sequence, as illustrated in Figure 1.

<u>HULLTECH</u>

HULLTECH is the latest generation of ship design software from the BMT Group (formerly the British Ship Research Association), which has been involved in the development of computer-aided ship design and production software for over 25 years. HULLTECH is a follow-on to BRITSHIPS 3.

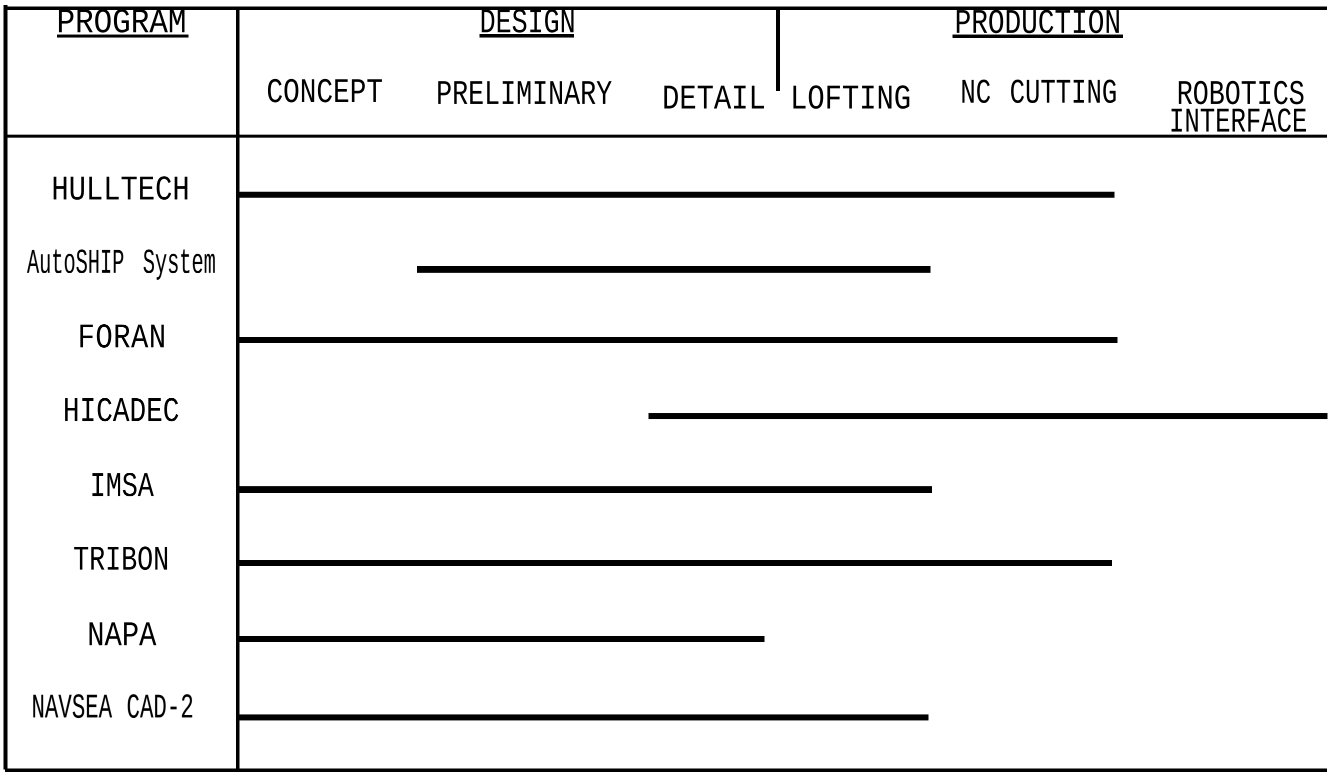

Figure 1 - Ship Design Programs' Focus in the Design/Production Sequence

HULLTECH supports the ship design process from initial concept design to providing production information. The software, initially written to run on mainframes, is now widely available on UNIX workstations and personal computers (PCs) as a result of a policy of open systems programming and portability. The software is presently being adapted for use on MS-Windows for the PC and X-Windows/Motif for workstations (38).

HULLTECH covers a wide range of shipbuilding-specific applications for designers and production engineers, including hull shape design, arrangements, lines development hydrostatics, stability, longitudinal strength, resistance and power, seakeeping and maneuvering, shell plate and internal steelwork definition, as well as plate nesting and cutting information for production. The generic application areas such as drafting, pipework, and structural analysis, are covered by third partly software for which BMT provides direct interfaces. Some of the third partly software supported includes Microstation, AutoCAD or ComputerVision for the drafting functions, CADMATIC or Computer Vision for the piping and plant modeling functions, and MAESTRO, ANSYS or PATRAN for the structural analysis (1, 2, 3, 4, 38).

AutoSHIP System

Coastdesign, formed in 1980, is a Canadian company. Its ship design program, the AutoSHIP System, is applicable from the preliminary design stage through lofting, with capabilities in the areas of hull definition and fairing, weights, stability, hydrostatics, longitudinal strength, resistance, and power. Developed for use by small and mid-sized yards, the program aims to be user friendly and can run on PCs. The program is scheduled to run entirely on Windows by mid-1993 (5, 6, 7, 8).

FORAN

FORAN is a computer aided design/ computer aided manufacturing/computer aided engineering (CAD/CAM/CAE) ship design and production system developed by the Spanish company Senermar. The program FORAN is written in the English language and may be run on UNIX and VMS operating systems

and with X-Windows and OSF/MOTIF. The latest version, FORAN V30, covers all the aspects of general design, drafting, steel structure, machinery and outfitting design and production. More than 100 shipyards in 19 countries have been licensed to use FORAN (9, 10, 34).

HICADEC

HICADEC is the outgrowth of systems developed in Japan by Hitachi Zosen Corporation which were first used in the 1960s. HICADEC has been in use since 1986 and is more powerfull and user friendly than its predecessors. This program, which runs on UNIX workstations, is available under X-Windows, HICADEC addresses the integrated CAD/CAM design of ship structure, piping, outfitting, and electrical design through the use of a three-dimensionally processed database. The system also provides input to support robotic ship production tasking, described in a following section. In additio, the HICADEC system is designed to make extensive use of standards. At Odense Steel shipyard, the marketing agent for the system in the West and co-developer of the HICADEC system in use at the Odense yard, the Danish shipbuilding standards have been incorporated (11, 37).

IMSA

IMSA, or International Marine Software Associates, is a cooperative venture being carried out by several American firms to integrate five existing programs into modules of an integrated ship design program. The program has capabilities in hull design, propulsion design and analysis, hydrostatics, stability, structural design and analysis, lofting, and support for numerical cutting. The IMSA programs run on workstations and PCs (12, 13).

TRIBON

Kockums Computer Systems (KCS) has refined and marketed three integrated design programs worldwide AUTOKON, STEERBEAR and SCHIFFKO. Each of these programs was developed independently, beginning in the sixties. The programs run on International Business Machines (IBM) or Hewlett Packard (HP) workstations and are used during the final design and production stages for ships and offshore structures. They provide capabilities in the areas of steel design and production, lines fairing, piping, cableways and ventilation design (14, 15, 16).

In mid-1993, KCS introduced a new program called TRIBON. It contains selected features from all three of the present programs and builds on the technology of STEERBEAR. TRIBON has applications for hydrostatics, stability, longitudinal strength, lines fairing, steel design, piping, cabling, ventilation, foundation and accommodations, as well as production information. TRIBON is coded in Unix C++ and will run on a DEC VAX/VMS workstation. Later versions will run on HP and, if customer demand warrants, IBM workstations. TRIBON will be upward compatible from its present three programs, which will continue to be supported (16, 25).

NAPA

NAPA (the Naval Architectural PAckage) is a computer-aided ship design program developed in-house by Wartsila Corporation beginning in 1976. It builds upon ship design software experience developed in the Wartsila Helsinki Shipyard from the 1960s. The program is now maintained and marketed by the independent company Napa Oy. It was first used productively by Wartsila in 1982, and since 1984 has been sold to outside companies, including many of the major European shipyards and Det norske Veritas Classification A/S. The program is written in FORTRAN 77 and runs on a variety of computers, including Sun, VAX and HP Workstations, and 486 PCs. NAPA is used from the early stages of design through detail design, and, following construction, for development of a ship's documentation. Capabilities include general arrangements, capacity lists, hull form design and fairing, lofting, intact and damage stability, container loading, grain stability, weight and cost calculations, longitudinal strength, launching, resistance and power, seakeeping, and maneuvering (17, 18,19,20,21,22, 36).

NAVSEA CAD-2

NAVSEA CAD-2 is a relatively recent initiative being carried out by Intergraph Corporation under contract to the Naval Sea Systems Command (NAVSEA). It provides CAD/CAM systems and services to support the design, construction, maintenance, overhaul, alteration, and repair of Navy ships and shipboard systems. The eight-year software development and implementation effort was begun in 1991. CAD-2 is run on UNIX-based workstations. The organization of CAD-2 is reflected in Intergraph's Vehicle Design System (VDS), the commercial version of the program. VDS is comprised of three modules,

encompassing equipment design, structural systems design, and a routing package that includes piping, HVAC, and electrical raceway design (23, 24).

One thrust of the effort is to develop interfaces between existing ship design programs that NAVSEA has procured or developed and a single product model. That is, existing programs, such as SHCP, are not made part of CAD-2, but their information requirements and data transfer capabilities are being addressed by CAD-2. Certain existing programs may be updated as part of NAVSEA's overall approach to computerizing the ship design process, but fill integration of ship design programs into CAD-2 is not envisioned in order to continue to encourage vendor competition. CAD-2 will be ported to run on X-Windows. An example of a program that is already ported into X-Windows is SPIFFY, a structural section analysis program, which calculates section properties and certain non-graphic attributes (e.g., weight) of a sectional cut through an Intergraph CAD model of a Ship (24).

INTEGRATION

The ultimate goal of integrated ship CAD/CAM is the total integration of all processes, from early design through production. Although many U.S. shipbuilders have made investments of millions of dollars in CAD/CAM systems, the various aspects of the systems tend not to be integrated with each other. For example, a shipyard may have one CAD system for structural design and a different CAD system for outfitting design. Additional aspects, beyond design, that could be integrated with the design process include Computer Aided Process Planning (CAPP) and robotics.

Integration of a ship design program maybe viewed from two levels:

- Integration among the modules of a ship design program is the most basic level of integration. This level of integration means that the various modules of a program are designed to communicate and share data with one another to at least some extent. User interfaces may differ, and commonly this type of program cannot support combining results from among the various modules to make a unified presentation of the results. This level of integration is characterized by some as an interfaced system rather than an integrated system (36).
- The more advanced level of integration is by means of a product model, which is a detailed, three-dimensional description of the ship and its major systems. The product model is a common database that is shared by all the modules; that is, there is no need for data conversion among the modules.

  Usually is there is a single user interface.

These two levels are discussed in the following paragraphs, and examples are provided from the integrated ship design programs described above. It must be stressed that the examples are illustrative and not all-inclusive; that is, if one program is used as an example to illustrate a certain future, that does not mean that other programs also have the same feature. Space constraints and the complexity of the programs themselves prevent a fill listing of features or a detailed comparison among the programs.

Integration Among Modules

Typically, when a ship design program is synthesized from a number of previously separate programs, the first step is to provide integration among modules as a means to provide the data from initial steps in the design process as input to follow-on steps. The data is stored in different databases or datastores, each of which may have different format and access conventions. One advantage of integration among modules and separate databases (one for each module) is that other, independently-developed modules may be added without having to expensively modify the new module to conform to the format of the existing program. This provides flexibility to quickly incorporate new capabilities, and thus upgrade the existing program.

In HULLTECH, modular and modeling information is stored using direct access binary datastores appropriate to each application. Datastore accession is direct where appropriate to obviate intermediate file data transfer. For example, the hullform generation system creates geometry that can be immediately analyzed by the naval architecture package (4). In the case of the AutoSHIP System, the modules communicate by intermediary files resident on a single directory. Within the Windows® environment, Dynamic Data Exchange maybe used, and there are extensive cut and paste capabilities (especially useful in report generation). IMSA facilitates computer-based interfacing of its five modules with each other and with third party programs, and has established a common data specification called IDF or IMSA Definition File. This file is open (i.e., published) in order to make the

development of interfacing easy for third party programs. Thus, the user can choose which program to use for each application (IMSA or third party) with the knowledge that data can be shared between programs (35).

Product Model

A product model is an integrated database of an entire ship that supports the informational needs of engineering, design, and production. Early versions of this concept were usually tailored to a specific project, and were not broadly enough based to address the general integration of design data and process information that together define a ship. More modem versions of the concept are tailored to ship design and production, yet are general enough to be used for different ship projects. The NEUTRABAS product information model, under development by the European Strategic Program for Research and Development in Information Technology (ESPRIT) Project, is an example of this type product model (27).

TRIBON is based on the concept of creating a three-dimensional database product model of a ship or platform. This product model is the source for technical and administrative information, including drawings, weights, NC data, parts lists, stiffener lists, piping, and materials (28, 25). Presently, Coastdesign, is developing its version of the product model, called the Single Vessel Definition, which will allow one basic vessel definition to be used from the earliest stages of the design process through to the final manufacturing phase in the AutoSHIP System (29). The developers of FORAN view integration as perhaps the most important aspect to be considered in their ship design program. The FORAN product model is topological, that is, it includes not only the definitions of the various ship elements themselves but also logical connections to other, related, elements. With this approach, a change to one element automatically generates changes to related elements (9, 26, 34). The NAVSEA CAD-2 system also has a product model capability. Key to the success of that product model are its parametric libraries, in which every part, from pipe to foundations, is composed of intelligent macros, enabling them to be tracked and put together into their design assemblies (23, 30).

In NAPA a product model of a ship (called a ship model by NAPA) is created and updated to form an organized, uniform source of design information. This model addresses general arrangements, compartmentation, tank lists, and capacities. The model can provide any parameters that are related to the ship model or parts of the model. For example, the user can select a subset of objects that the model tracks, and receive data relating to that subset such as volumes, areas, or centers of gravity (21, 36).

Related Considerations

Related considerations for integrated ship design programs include flexibility for future growth, technical excellence of the modules, communication with other programs, and making the programs user friendly. Flexibility for the future has been noted as an advantage of a program that uses separate databases for each of its modules (although the use of separate databases has disadvantages as well in regard to user friendliness and efficiency of operation). The need for flexibility, even within common database and product model types of ship design programs, is recognized by a number of program developers.

Technical excellence in the modules of ship design programs is another area of focus. Technical excellence forms the foundation on which the validity and usefulness of the programs are based. An example of technical excellence is found in MAESTRO, a module in the IMSA program. MAESTRO carries out structural finite element analysis, failure mode evaluation and multi-objective optimization. The program applies to ships, advanced and high performance vehicles, offshore structures and submarines. MAESTRO has been successfully validated against other programs and physical experimental results, and is in use worldwide.

Communication with other vendors' programs and databases is of increasing importance in today's environment of computer-based information exchange. This kind of communication is important in the shipbuilding environment when, for example, the contract design is produced with a ship design program that is different from the one on which the final design is to be developed. HULLTECH interfaces include IGES, DXF, and PATRAN (38). The AutoSHIP System interfaces with other programs through Data exchange Format (DXF) and Initial Graphics Exchange Specification (IGES). FORAN software can interface with other systems using DXF, SIF, IGDS and HPGL formats (31). As noted above, IMSA has published its common data specification, IDF, as a means to foster communication with other programs. HICADEC communicates with other CAD systems using DXF and IGES, and is linked to BMT Hullsurf, NAPA, among others (37). IMSA output and input may be in various formats, including DXF, SHCP and IGES. KCS' USS is designed to be open by providing

DXF and IGES interfaces and communication capabilities with the STandard for the Exchange of Product data (STEP) Program. It provides input to Det norske Veritas for classification. Over 20 interfaces are available to and from NAPA, including IGES, VDAFS (German Standard DIN 66301), DXF, MEDUSA SCHIFFKO, AUTOKON, TRIBON and a direct on-line link to STEERBEAR (25, 36). CAD-2 interfaces include IGES, CALS-IGES and DXF. STEP will be addressed also (30).

A final consideration is making programs user friendly. For example, a user friendly feature in the IMSA module FAST SHIP is in the area of hull design, where a designer works interactively with the computer and "sculpts" surfaces of the hull. In this way, the designer watches the hull shape change dynamically as control points are moved in three dimensions. The program also carries out hydrostatic calculations, giving the designer immediate feedback that target hydrostatic values are being matched (12, 13). To help make NAPA user friendly, emphasis has been placed on enhancing the user interface through ease of learning how to use the system on-line help functions and an interactive, command driven format. NAPA's flexibility in use, excellent graphics and uniform user interface, and the totally integrated modem structure, in short, its ability to be user friendly, formed the basis for a major classification society choosing NAPA as its naval architectural program (19). Other programs also have features that help make them user friendly.

ENHANCING SHIP PRODUCTION

A powerful potential advantage of integrated ship design programs is that the data generated during the design process can be tailored in format and content so that it can help support the ship production process. Virtually all of the programs described above provide at least some input to the ship production process, and several programs provide significant input.

HULLTECH uses interactive facilities and computer graphics to provide shell plate surface curves (e.g., seams, butts and longitudinal traces), and a breakdown into individual plates for their development complete with all marked-on lines (2-dimensional definition, green, minimum rectangle, sight line templates, and pin-jig bed). HULLTECH also provides relevant production information for shop floor personnel and information that supports interactive nesting and automatic NC path generation. Inverse frame-line bending data is included for both longitudinals and transverses (32). CAD-2 support to the production process includes plate nesting capabilities (including the ability to address doubly contoured plate, and to include NC cutting lines as well as sight lines) and NC pipe bending and production instructions (30). Coastdesign plans to extend its AutoSHIP System capabilities to defining shapes, but not to NC cutting and robotics, preferring to leave those functions to third-party systems (8).

FORAN provides information for use in steel production, and in machinery and outfitting production. In the case of machinery and outfitting production, FORAN's capabilities include automatic 3-D generation of fittings as parametric objects; equipment 3-D solid modeling layout of equipment, ducts, cable trays, piping, and similar systems with respect to the steel structure or any other component full integration of diagram information with the 3-D module definition, on-line interference detection, and, finally, the generation and handling of manufacturing and assembly documents, from parts lists to bills of materials (9).

HICADEC places great emphasis on supporting the ship production process, with information provided to name, describe and specify exact cutting and assembly operations to the level of individual parts. Odense Steel shipyard has used HICADEC on several recent commercial new construction projects. On these projects the system automated the production of steel detail and outfitting fabrication and assembly drawings; automated the detail planning and budgeting for steel work and automated material takeoff and requisitioning. It also created a structural database from which the automated welding programs for a series of very large crude carriers (VLCCS) (prepared by one person) which resulted in the automated weldlng of 100% of the midbody sections by Odense welding robots (33).

IMSA'S modules ShipCAM and NC-PyrosLofting address development of the table of offsets through all stages of fairing and lofting to the NC code for computerized plate burning. The program is interactive, and all surfaces can be expanded to flat plate with all markings for frames, stringers, bulbs, or thrusters.

KCS' TRIBON provides tools to plan the assembly stage of production for hull and outfit items. The TRTIBON structural system handles comprehensive bracket generation, nesting of plate parts, workshop drawings and production information, parts and profile lists, templates for bending plates and stiffeners, and assembly jig data. TRIBON'S outfitting system covers standard material and specification libraries, schematic diagrams, equipment definition and location, modeling of pipes, cableways and ventilation ducts, isometric

drawings, material lists for prefabrication and assembly, weld records, NC bending data, interference control, weight and center of gravity calculations, and composite drawings. The electrical modules cover the areas of cable specification and registration, equipment definition and location, cableway registration, automatic routing of cables, and installation instructions and feedback.

CONCLUSIONS

Integrated ship design programs, based on experience and lessons learned since initial applications in the 1960s, are providing real-world enhancements to ship production and, as improvements are continually added, will continue to do so. The trends include further integration through product models, enhanced communication with third party programs, increased user friendly interfaces, and the extension of program capabilities into early stages of design and into production.

REFERENCES

1. 'Overview of BMT Software for Marine Applications, 'BMT ICONS Limited, Wallsend Research Station, Wallsend, Tyne and Wear, England.
2. 'Conceptual Design and Tendering Software,' BMT ICONS Limited, Wallsend Research Station, Wallsend, Tyne and Wear, England.
3. Telephone Conversation with Graham Marshall (BMT ICONS Limited), April 8, 1993.
4. Fax Message from Graham Marshall (EMT ICONS Limited), April 15, 1993.
5. Coastdesign Marine Software Product, Surrey, B.C. Canada, May 15, 1992.
6. AutoSHIP System, The Industry Standard, Coastdesign, Surrey, D.C. Canada.
7. AutoCLASS, Coastdesign.
8. Telephone Conversation with Grahame Shannon (Coastdesign), April 1, 1993.
9. Letter from E. Martinez-Abarca (Senermar), April 14, 1993.
10. 'Shipyard Week - Senermar Turns to UNIX to Widen Market,' *Lloyd's List*, February 3, 1993.
11. Inoue, Takehiko, Hirotaka Shirakami, Kunihiko Shishida, Younosuke Moriya, "HICADEC: Integrated CAD/CAM System With 3D Interactive Data Processing Architectures for CIMS in Shipbuilding," *Computer Applications in the Automation of Shipyard Operation and Ship Design, VI*, D. Lin, Z. Wang and C. Kuo (editors), Elsevier Science Publishers B.V. (North-Holland), IFIP, 1989.
12. IMSA, International Marine Software Associates, Durham, NH.
13. 'Proposal to Develop an Integrated Ship Design Optimization Tool (ISDOT), Technical Proposal, Volume I,' Ross-McNatt Naval Architects, Annapolis, MD, November 6,1992.
14. Kockums Computer Systems is Your Long Term Partner, Kockums Computer Systems AB, Malmo, Sweden, 1990.
15. AUTOKON, Kockums Computer Systems AB, Malmo, Sweden, 1989.
16. Meeting with Ove Eng (Kockums Computer Systems), Washington, DC, March 26, 1993.
17. NAPA Documentation/Main System/General, System Functions of NAPA, Napa Oy, J. Saarilahti, 1991.
18. 'New Company for the Challenges of the 90s,' *Shipping World & Shipbuilder*, p. 30, January/February 1990.
19. 'NAPA for Det norske Veritas,' *Schiff & Hafen/SEEWIRTSCHAFT*, Heft 8, p. *39*, 1991.
20. Telephone Conversation with Ilmo Kuutti (Napa Oy), April 5,1993.
21. Kuutti, Ilmo, "NAPA, The Naval Architectural Package for Professionals," Napa Oy, November 18, 1991.
22. 'NAPA, The CAE system for Basic Ship Design,' *Shipping World & Shipbuilder*, October 1989 [check this date].
23. Donovan, Rick, "NAVSEA CAD-2 1993 Program Status and Highlights; Full Speed Ahead in a Successful Transition," Intergraph Corporation, Federal Systems Division, March 1993.
24. Telephone Conversation with James Murphy (Naval Sea Systems Command), April 1, 1993.
25. Fax Message from Ove Eng (Kockums Computer Systems), June 17, 1993.
26. 'FORAN V30, The Way to CIM from Conceptual Design in Shipbuilding,' Senermar, Sener Sistemas Marines, S. A., Madrid, Spain.
27. Welsh, M., J. Lynch, and P. Brun, 'A Data Model for the Integration of the Pre-commissioning Life-cycle Stages of the Shipbuilding Product; The Society of Naval

Architects and Marine Engineers 1991 Ship Production Symposium, San Diego, CA, September 3-6, 1991.
28. Letter from Henrik Bucher (Kockums Computer systems AB) to Tobin R. McNatt (Ross-McNatt Naval Architects) dated February 4, 1992.
29. Shannon, Grahame, 'Visions of the Future,' *Productivity Tips*, Volume 1, Issue 1, Coastdesign, Surrey, B. C., Canada, May 1992.
30. Telephone Conversation with Stephen Klomparens (Intergraph Corporation), April 5, 1993.
31. 'Sotftware Suppliers Seek Increased Integration,' The Motor Ship, p. 56, April 1993.
32. BMT ICONS Brochure, BMT ICONS Limited, Wallsend Research Station, Wallsend, Tyne & Wear, England.
33. Martin, Doug, 'Acquire, License to U.S. Shipbuilders and Support the HICADEC Shipbuilding CAD/CAM System,' 1993 NSRP Project Abstract, November 30, 1992.
34. Fax Message from E. Martiniz-Abarca (SENERMAR), June 15, 1993.
34. Fax Messages from E. Martiniz-Abarca (SENERMAR), June 15,1993.
35. Fax Message from Bruce Hays (Design Systems & Services, Inc.) to Tobin R. McNatt (Ross-McNatt Naval Architects), June 7, 1993.
36. Fax Message from Ilmo Kuutti (NAPA Oy), June 21, 1993.
37. Fax Message from Torben Andersen (Odense Steel Shipyard, Ltd.), June 22, 1993.
38. Letter from Chris. J. Lloyd (BMT ICONS Limited), June 16, 1993.

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On the Job Training in Line Heating in Astilleros Espanoles Shipyards, A Profitable Experience

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ABSTRACT

This paper describes the experience in teaching Astilleros Españoles(AESA)' steel fabrication workers in the practical use of line heating (L/H) for accurate bending of plates, and the operational deployment of this technology in all shipyards in the group. This project is set within the developing dimensional accuracy improvement program, which is aimed at improving productivity, quality and allowing the implementation of a continuous improvement process.

The approach used is for facilitating a systematic technology transfer from Japanese specialists, *overcoming* initial reluctance, promoting active participation with a commitment from workers and foremen, and assuring practical documentation of experiences in the form of a shop operating manual.

THE ACCURACY TARGET

In April 1990 a key document for the ongoing technological change was issued by the group's top management under the name of PIMET, which stands for "Plan Integral de Mejoras Tecnológicas" (Global Plan for Technological Improvement)(l). This document established the Japanese shipbuilding industry as a model of reference, and emphasized its main logic and principles.

The PIMET consistently recognized accuracy control (A/C) as one of the main elements for achieving world class productivity, and required each one of the group's shipyards to establish A/C related projects. One of these projects was the development of the operating capacity for forming plates by line heating, with the purpose of producing accurate parts for the downstream users.

L/H for fairing purposes was introduced in Spain around 1956 by a Finnish Company called TAMPO. Since then distortion removal was done by workers known as "TAMPO specialists", but in all that time L/H had rarely been used for bending purposes, and only as an auxiliary technique at the steel fabrication shops. Furthermore, due to the non-systematical process of knowledge transfer and the lack of written procedures, most of the profitable know-how was unfortunately lost for the time that the PIMET was issued.

THE FIRST APPROACH SHIPYARDS SELF-TRAINING AND IMPLEMENTATION

As pointed out by Messrs. R. Gutiérrez and A. Sarabia (2), the NSRP of the U.S. has been an extraordinary source of information to AESA, both for identifying development opportunities and designing ad-hoc policies, as well as for preparing internal documents on key technical topics. From that source succesful results obtained in some U.S. shipyards on L/H training were "discovered", and a publication (3) on the practical use of this technique, which in November 1990 was translated into Spanish, was released to all shipyards as a guide for self-training. However, after several months no progress had been made and only a few shipyards had made some erratic and unsuccessful trials.

LOOKING FOR A GUIDED IMPLEMENTATION THE TESTING PROGRAM AT SEVILLA SHIPYARD

To solve the difficulties which appeared to arise at the shipyards in implementing L/H practices, and to give them enough confidence to proceed by themselves, company's top management decided to launch a systematic program of practical L/H experiences based at one of the shipyards, concentrating all necessary internal and external support. The program would be managed by the Industrial Development Department at the company's head office. Sevilla shipyard, reputed as a pioneer in introducing many technological changes in Spanish shipbuilding history, was chosen for that purpose. In April 1991 a kick-off meeting was held with all responsible persons from the different shipyards.

The first phase of the program covered checking and measuring bending and shrinkage effects, identification of more efficient combustion parameters, torches, tips, travel speed and flame-plate and flame-water distances, the effects of jigs and of mechanical stressing by dogs and wedges, and the study of the metallurgical and mechanical conditions left by the heat inputs and stresses involved in L/H processing. All the

tests were made on plate samples of different thicknesses covering applicable ranges.

From the results of this phase the following was established.

1. The use of large flame (aprox 800 mm.) propane Harris torches,

2. The use of type M Koike tips models L-4000 for thickness lower than 10 mm, and L-5000 for higher thickness,

3. The use of a torch tip to plate distance (Table I) in between 20 and 28 mm depending upon the plate thickness,

4. The use of a water jet to flame distance of about 100 mm. when water cooling were to be applied on the same plate face than heating.

Working under these conditions the maximum temperature (measured by thermocouples at 2 mm. below the surface) does not exceed 650°C. Thus L/H forming does not induce any major deterioration on the plate material and the resultant toughness (Table II) is not lower than that associated with forming, for example, by roller.

MATERIAL	GROUP	THICKNESS (mm.)	OPTIMUM TIP-PLATE DISTANCE (mm.)
ORDINARY-STRENGTH STEEL. GRADE A	1 2 3 4	12:14 15:18 19:24 25:40	20 20 20 28
HIGHER-STRENGTH STEEL. GRADE AH	1 2 3	14:15 16:18 19:20	20 20 20

Table I: Optimum tip-plate distance

FORMING BY	MICRO-STRUCTURE	TEMPERATURE °C	CHARPY IMPACT TEST (J) (notch on plate surface)		
			1	2	3
ROLLER	FERRITE-PEARLITE	ROOM	122	297	282
L/H	FERRITE-PEARLITE	720°C	246	278	298

Table II: Ordinary-strength steel, grade A, thickness 14 mm.

Other practical results obtained *were:*

1. Combustion parameters and torch travel speeds to use to limit a maximum temperature to 650°C without loosing bending efficiency (Tables III and IV),

2. What levels of bending and shrinkage could be expected (Tables V and VI) for many of the possible combinations plate thickness/-plate quality/torch travel speed,

3. The effects of succesive superimposed heat lines,

4. How to use wedges and dogs efficiently to control and correct curvature.

GROUP #	THICK NESS (mm.)	PRESSURE (kg/cm^2)		FLOW (L/H)		OPTIMUM TORCH TIP-PLATE SEPARATION (mm)	MINIMUM TORCH-SPEED (mm./min.)
		PROPANE	OXYGEN	PROPANE	OXYGEN		
1	12:14	0.8	5.8	1.500	7.000	20	400
2	15:18	0.8	5.8	2.200	10.000	20	300
3	19:24	0.8	5.8	2.600	13.000	20	300
4	25:40	0.8	5.8	3.200	16.000	28	250

Table III: Ordinary-strength steel, grade A.

GROUP #	THICK NESS (mm.)	PRESSURE (kg/cm^2)		FLOW (L/H)		OPTIMUM TORCH TIP-PLATE SEPARATION (mm)	MINIMUM TORCH-SPEED (mm./min.)
		PROPANE	OXYGEN	PROPANE	OXYGEN		
1	14:15	0.8	5.8	1.500	7.000	20	300
2	16:18	0.8	5.8	2.200	10.500	20	300
3	19:20	0.8	5.8	2.800	13.500	20	300

Table IV: Higher-strength, grade AH.

Finally, people involved in this first phase were able to design basic line heating procedures for some simple forms, including number of lines and torch travel speeds to be applied, and to perform them successfully.

The second phase of the testing program (which took place in two different shipyards) was mainly devoted to screen triangular heating/cooling cycles and the fracture toughness of the materials. When L/H forming schemes include triangle heating, Tables VII and VIII show that heating up to a temperature of 900°C and water cooling once the temperature is at or below 500°C does not reduce toughness below the minimum required by standards. However, from the point of view of that material characteristic, it would be much better to work with temperatures not exceeding 850°C.

Both experimental phases were thoroughly documented, and the different documents were sent to all shipyards to be released to their steel fabrication shops. Pertinent people were directed to study them, fabricate some simple forms following basic L/H principles and operations, there contained and record any difficulties they encountered.

After this the different shipyards appeared to be confident with the technique, and prepared to "learn the practice".

GROUP #	THICK NESS (mm.)	TORCH SPEED (mm/min.)	TEMPER ATURE °C	ANGULAR DISTORTION (degrees)
1	12 14	400 300	500 550	1,3 1,2
2	15 16 18	300 300 300	500 500 500	1,0 1,0 1,0
3	19 20 22	300 250 200	500 600 600	1,2 1,1 1,0
4	25 28 30 40	200 250 250 250	600 500 500 500	1,3 1,0 0,9 0,6

Table V: Ordinary-strength steel, grade A.

GROUP #	THICK NESS (mm.)	TORCH SPEED (mm/min.)	TEMPER ATURE °C	ANGULAR DISTORTION (degrees)
1	14 15	300 300	500 500	1,1 1,0
2	16 17 18	300 300 300	500 500 500	1,2 1,2 1,1
3	19 20	300 300	500 500	1,2 1,0

Table VI: Higher-strength, grade AH.

SPECIMEN	ZONE	TEST TEMPER ATURE	ABSORBED ENERGY (J)	IMPACT STRENGTH (mm)	DUCTILE FRACTURE
A-1 (14 mm.)	HEATED	0°c	72	1.06	50%
	NON HEATED	0°c	111	1.43	60%
A-2 (28 mm.)	HEATED	0°c	46	0.78	55%
	NON HEATED	0°c	88	1.36	85%

Table VII: Fracture toughness test results. Ordinary-strength steel, grade A. Minimum required value according to ABS 27.4 J. for plate thickness ≥2" at 20°C.

SPECIMEN	CHARPY V-NOTCH ASTM A-370	NOTCH ON SURFACE
	ABSORBED ENERGY (J)	ABSORBED ENERGY (J)
Before Forming	105	180
After Rolling Long Radius Side	102	172
After Rolling Short Radius Side	97	183
Triangle at 900°C Water cooling < 400°C	109	162
Triangle at 900°C Water cooling < 500°C	62.5	158
Triangle at 900°C Water cooling < 600°C	21	98
Triangle at 850°C Water cooling < 500°C	98	
Triangle at 800°C Water cooling < 500°C	88	
Triangle at 750°C Water cooling < 500°C	96	
Triangle at 700°C Water cooling < 500°C	94	

Table VIII: Fracture toughness tests results. Higher-strength steel, grade AH-36. Minimum required value according to ABS 34 J. at 0°C.

THE JAPANESE ARRIVAL TO SESTAO SHIPYARD

Knowing from the Journal of Ship Production and some NSRP technical publications of the important role played by Ishikawajima-Harima Heavy Industries in shipbuilding technology transfer to the U.S. during early the eighties, it was considered beneficial for the company to incorporate Japanese consultants to support the development of the PIMET. Following recommendations of Mr. L.D. Chirillo, Maritech Engineering Japan Company (MEJ) was contacted.

In May 1991 was asked to visit Sestao shipyard in order to evaluate its production system. It soon became clear that the company could benefit from these consulting services. In October an agreement was signed for a two-year term to support a shipyard productivity improvement project; L/H Skill development was one of the issues where support was immediately required.

The first L/H demonstration sessions by the Japanese experts took place at the end of June in Sevilla shipyard, where a company testing program was being developed with the help of Spanish consultants.

THE TRAINING PROGRAM GOALS AND PRINCIPLES

Goals

From the very beginning the training program was targeted to fulfill three main goals:

1. Deploy the L/H technique throughout all of the group's steel fabrication shops in a short period of time,
2. Promote awareness among workers and foremen of the critical importance of accuracy, and
3. Develop a practical shop L/H Operating Manual in order to assure the control of the know-how in the company and so to guarantee the quality of the training of new workers.

The training had to cover workers and foremen from many shipyards. In total about thirty five people

were chosen, who would later spread their knowledge among other teams in the shipyards.

The objective was to train skilled workers, very much attached to the use of rollers and presses, and traditionally more concerned with productivity than accuracy. Because of this, the emphasis at this stage had to be accuracy.

Documenting all the training experience in detail in a practical way was considered necessary to the project, in order to avoid losing the new technique. The importance of assuring to owners and classification societies that quality requirements are met through appropriate controls in the shops on plate heating and cooling conditions was covered by the training system documents. Therefore, appropriate tests were established to determine practical operating and control conditions.

Principles

The L/H training program was established according to the following principles.

1. It would be basically organized as on-the-job training sessions at the lead shipyard under the control of the L/H Japanese expert, with practice periods at each of the other individual shipyard.

2. Classroom sessions would be held at the end of each training period at the lead shipyard, and at any other time deemed necessary. All workers' questions would be systematically gathered before each session and addressed to the expert.

3. The training program would take place during a fifteen-month period, with five two-week long sessions led by the Japanese expert.

4. The program should progressively cover plates of all grades of difficulty.

5. The group's head office would coordinate the program through its development department, including the continuous evaluation of the progress, and implementation of necessary feed-back actions.

DOCUMENTATION, THE L/H OPERATING MANUAL

In order to assure the systematic documentation of L/H technology, and the preparation of the L/H operating manual (4), a Spanish consultancy firm already working in the L/H practical experiences program at another shipyard was assigned to perform the documentation task.

Operating procedures followed by the expert were fully documented and distributed to every shipyard. Representative examples of plates of different degrees of difficulty were used. Procedures included a step-by-step description of each plate bending history, accompanied by photographs and detail figures. The same procedure was followed for documenting the more representative classroom questions and answers.

As a result of this documentation effort, an L/H operating manual was prepared, aimed to facilitate the training of the foremen and workers at the steel fabrication shops. The manual was distributed to the shops, and meetings were held at each shipyard to review the main concepts; these meetings also guaranteed that the workers read the document. A draft of the manual already had been sent to the shipyards for comments.

The manual covers, in a simple shop language all the necessary information: from very general concepts and techniques, to very detailed practical solutions to particular cases. The main sections of the manual are:

- Basic Principles,
- Required Facilities,
- Heating and Cooling Conditions,
- Temperature Control,
- Sight Line Templates,
- Heat Application Techniques, and
- Forming Criteria and Schemes.

The Manual will be kept current through a periodic review process that will guarantee the incorporation of the accumulated experience of all the shops.

WORKER'S ATTITUDE

The L/H project was viewed favorably by shipyard representatives at the kick-off meeting held in April 1991. However this good disposition was accompanied by a certain concern about the capacity of the company to develop and implement the L/H technology without external support.

The support of outside experts and specifically, their knowledge, experience, authority and commitment has been the key for the quick deployment of L/H in the various shops. However it must be pointed out that just following systematically the NSRP L/H technical document would allow any shop to begin practicing the technique.

The attitude of the workers and foremen for learning this new technique has been in general very positive. Since the first demonstration in June 1991, they have participated very actively in the training sessions and implemented the technique in real production in their shops, with the strong support of the

shop managers. The L/H operating manual has benefited greatly from their acute observations and feedback on practical operating details.

FUTURE WORK

Short term

Although the L/H technique is in general operative in all of the group's shipyards, the level of expertise and/or fulfillment of capacity needs are not yet totally satisfactory in some shipyards. Because of this, new on-the-job training courses are being developed to solve the problems.

From now on, the shops will have to concentrate on improving efficiency through a better combined use of L/H and of cold forming with available mechanical means. Also, they will need to follow the L/H operating manual recomendations and their own accumulated experience.

Accuracy, which is being statistically tracked, will be further improved through better template construction, and implementation of new procedures to diminish errors in the setting of angles with plates.

The public yards are also helping all privately owned Spanish shipyards to introduce L/H in their bending shops.

Long term

As part of the FASP (Flexible Automation in Ship Prefabrication)[1], research has begun on the design and construction of a line heating system for semi-automatically forming hull plates to a predetermined shape. The system development is planned for operation by a worker highly skilled in manually applied L/H. The CNC system is thought to be programmed on-line.

The system will be provided with manual plate clamping and stressing means, and a vision system for automatically measuring plate deformation at each bending process step. The system will be linked to a CAD system through the appropriate interface.

CONCLUSION

The results of this fifteen-month training program have been very satisfactory. Technology transfer was finished last September, and the skill level of our workers, especially in the case of Sestao shipyard, has been rated by the Japanese consultants as equivalent to a Japanese worker with five years of experience.

Assembly section workers recognized major improvements in plate accuracy: this has not only increased assembly productivity, but has also contributed to a more self-demanding attitude of the assembly workers with respect to their own work accuracy. Improvements in quality of assembly plattens, and demands for a better assembly-finished-curved-shell-marking procedure, are examples of this new attitude.

Another PIMET project that has benefited from the success of the L/H project is the Fairing Heat project. This project has followed the same kind of approach, and has received the invaluable support of Japanese experts.

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REFERENCES

1. PIMET. Plan Integral de Mejoras Technológicas (Global Plan for Technological Improvement) Astilleros Españoles, Madrid 1990 (In Spanish).

2. R. Gutiérrez and A. Sarabia, "A Return to Merchant Ship Construction: The International Impact of the NSRP and American Technology," 1991 Ship Production Symposium.

3. IHI Marine Technology, Inc., for Todd Pacific Shipyards Corp., "Line Heating" November 1982.

4. AESA'S Line Heating Operating Manual (Spanish and English versions).

1 *The FASP project is part of the European Eureka program aimed to keep European shipyards competitive.*

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Naval Shipyard Machine Shop Modernization

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ABSTRACT

The Naval Shipyard Corporate Operations Strategy & Plan (COSP) defines the vision, goals, and strategies for achieving excellence in shipyard business and operations. The COSP establishes an action for the "Modernization of Naval Shipyard Inside Machine Shop (shop 31) Practices and Procedures." This paper describes the Naval Sea Systems Command's (NAVSEA) initiative to provide the inside machine shops with the management systems and industrial technologies to meet the challenges of the 21st century. The Shop 31 Modernization Corporate Master Plan addresses. the functional areas of equipment, facilities, integrated management systems, human resources, shop operations, and customer/ supplier interface processes. This plan is presented as a benchmark for consideration in shop modernization efforts in U.S. shipyards.

INTRODUCTION

The mission of the eight Naval Shipyard Shop 31's is to safely perform assigned in-shop machining, manufacturing, repair, and test work within schedule and cost with first time quality. This is performed in support of the total shipyard mission to repair, overhaul, and modernize surface ships and submarines of the U.S. Navy fleet.

The inside machine shop represents the central core of the shipyards' industrial capability. Every other shop in the shipyard is directly or indirectly a customer of inside machining operations. Any delay, rework, or other problems that occur in shop 31 generally have a compounded, "snowball" effect that increases waterfront costs and time.

Background

The specific problems and strengths of naval shipyard inside machine shops have been documented. This was accomplished by shipyard industrial engineering studies and by surveys conducted by the National Institute of Standards and Technology (NIST). The findings revealed that shipyard machine shops were limited in their ability to meet today's stringent technical requirements in an efficient and cost-effective manner. Plant equipment inventories, industrial processes, and management systems were not kept current with the latest machine shop technologies available. Much of the shops' plant equipment was predominately single function, manually operated, and outdated machine tools that could not be economically maintained.

In recognition of these problems, individual naval shipyards had initiated several projects aimed at modernizing shop 31. Examples of these shipyard initiatives include a small parts flexible manufacturing cell at Charleston Naval Shipyard, an automated shop production management system at Norfolk Naval Shipyard, a group technology and computer aided process planning project at Mare Island Naval Shipyard, modernization of propellor manufacturing technology at Philadelphia Naval Shipyard, a quality measurement and tracking system at Puget Sound Naval Shipyard, the initial NIST machine shop survey at Pearl Harbor Naval Shipyard, integration of project management at Long Beach Naval Shipyard, and a fastener manufacturing cell at Portsmouth Naval Shipyard, An automated Shop Floor Control system for all shops was initiated by the Naval Shipyard Production Officers.

Corporate Operations Strategy & Plan

The COSP was issued in May 1990, and formally established modernization of Shop 31 as a priority strategic naval shipyard requirement. The COSP called for development and implementation of a Shop 31 Modernization Corporate Master Plan. While the initial COSP focus for modernization of production shops was on Shop 31, it was intended that many of the results and products would have direct application and/or benefit to other shops.

As the NAVSEA/naval shipyards' strategic plan, the COSP established many other corporate initiatives which are directly contributing to the improved performance of the inside machine shops. A thorough correlation analysis was completed to define the alignment and integration of the COSP with Shop 31 modernization. The most significant COSP actions include the re-engineering of core shipyard business processes and systems in the Advanced Industrial Management (AIM) Program, the naval shipyard reorganization reflecting the transition to a project management focus on the product, installation of local area networks (LAN) in shipyards, and Total Quality Leadership (TQL) continuous improvement initiatives.

Shop 31 Modernization Process Action Team

Consistent with TQL principles and techniques, a Process Action Team (PAT) was established to accomplish the development, implementation, and continuous improvement of the Shop 31 Modernization Corporate Master Plan and associated actions. The Shop 31 Modernization PAT, which first met in August 1990, includes two members from each naval shipyard (one person each from the inside machine shop and production/industrial engineering), as well as representatives from NAVSEA headquarter's organizations. The PAT also has advisory members from NIST, the Air Force (Oklahoma city Air Logistics Center), and the Army (Watervliet Arsenal).

SHOP 31 MODERNIZATION CORPORATE MASTER PLAN

The Shop 31 Modernization Corporate Master Plan was issued in November 1991. This plan establishes a comprehensive, systematic approach to the modernization of all eight naval shipyard inside machine shops. The plan identifies actions required to provide inside machine shops with the skills, facilities, equipment, processes, and systems needed to ensure efficient and effective operations and quality products, and to support continuously improved performance of the overall shipyard mission. It is the corporate baseline to guide the development and implementation of a tailored plan at each naval shipyard. Each shipyard's plan will specifically address their modernization needs and priorities, recognizing the differences in the shipyard's workload, workforce, and their current relative state of modernization. At the same time, the Corporate plan standardizes optimum systems/processes across all shops, and integrates the individual shipyard initiatives for replication.

The shop 31 Modernization Corporate Master Plan is not limited to "inside the walls of the inside machine shop," nor is it simply suggesting that shops buy the latest, greatest machine tools. The plan encompasses modernization of all internal and external functional, organizational, informational, and material inputs, processes, systems, and outputs affecting Shop 31 operations.

The guidance of NAVSEA headquarters and the initiatives of the Shop 31 Modernization PAT have driven a top-down approach to plan development. At the same time, the prior and concurrent modernization initiatives of the individual shipyards, including development of each shipyard's plan, have provided a bottom-up foundation.

Functional Areas:

The following six functional areas provide the framework for the Shop 31 Modernization Corporate Master Plan. The functional areas are the top level machine shop attributes for modernization. They represent the overall answers to the basic question associated with development of the master plan – "what do we modernize in order to improve Shop 31 mission performance?" Each functional area has direct interfaces with the other functional areas at varying levels.

1. Equipment,
2. Facilities,
3. Integrated Management Systems,
4. Human Resources,
5. Shop Operations, and
6. Customer/Supplier Interface Processes.

For each functional area, the Corporate Master Plan's content is as follows:

1. Definition: a brief statement of what the functional area entails and addresses;

2. Goal: a general statement of the desired outcome to be achieved for that functional area; and

3. Objectives: a listing of the basic changes and actions required in order to achieve the functional area goal. Each shipyard will include additional local objectives in their shipyard plan to address internal modernization needs and improvement opportunities.

The plan also establishes an outline of the specific actions and schedule required to be implemented in order to achieve the objectives. The completion dates are the corporate target dates, but individual shipyard priorities will vary based on unique needs and conditions. Certain actions are being managed corporately, and may be prerequisites for an individual shipyard action for that objective. Many of the objectives are on-going actions.

Performance measures are also part of the plan. These performance measures enable the tracking of progress towards meeting the goals and objectives. More importantly, they provide information and data on which to base continuing improvement actions.

Outline of Master Plan Functional Areas

The following section is an outline of the definition, goal, and objectives for each of the functional areas.

I. Equipment

A. Definition: All Industrial Plant Equipment (IPE), tooling, fixtures, test equipment, measuring tools, and other support equipment used in the manufacture, repair, assembly and test of ships components assigned to the Inside Machine Shop.

B. Goal: Provide the Inside Machine Shops with an inventory of modern capital equipment technology with flexible capabilities to meet present and future production requirements.

C. Objectives:

1. Identify shop equipment capability and capacity needs based on future workload, parts mix, group technology, cell technology, and work flow.

2. For the existing machine tool inventory, determine planned utilization, and program for disposal as excess, rebuild or retrofit, replacement, or retention.

3. Develop a long range capital investment plan for machine shop equipment modernization.

4. Implement an effective machine tool preventive maintenance program, including diagnostics.

5. Improve tooling and fixture technology, application, and inventory control, and other actions to reduce equipment set-up time and maximize productive time "cutting chips."

6. Increase the level of standardization in machine tools and NC controllers across all shipyards.

7. Improve the capability and applications of equipment programming, including transferability of programs across shipyards.

II. Facilitie

A. Definition: Inside Machine Shop structures, utilities, weight handling equipment and environmental controls supporting shop operations.

B. Goal: Upgrade and maintain Shop 31 facilities to improve Shop 31 mission effectiveness.

C. Objectives:

1. Develop and implement a comprehensive, consolidated, prioritized Shop 31 facility upgrade and maintenance plan, including utility systems

2. Implement a shop cleanliness policy and program.

3. Evaluate and upgrade machine tool installation procedures, including foundations and utilities.

4. Evaluate and upgrade material storage and handling facilities, including overhead lift equipment.

5. Evaluate and upgrade environmental controls within shop areas to support machining and inspection operations.

III. Integrated Management Systems

A. Definition: Information systems to plan, schedule and manage the workload and resources of the Inside Machine Shop.

B. Goal: Provide timely, accurate information to make management decisions to satisfy customer requirements. Develop and implement a flexible computer integrated repair/manufacturing system which integrates shop planning, group technology, computer aided process planning, CAD/CAM, shop floor control, scheduling, organizational structure, and performance measures; interfaces with customers and support organizations; and supports AIM.

C. Objectives:

1. Develop and implement a standard Shop Floor Control system. This includes installation of a Shop 31 Local Area Network (LAN) interfacing with the shipyard LAN.

2. Complete a parts mix study to reflect future planned workload.

3. Implement a group technology based computer aided process planning system.

4. Implement Distributed Numerical Control (DNC).

IV. Human Resources

A. Definition: The people and their skills, training, safety, and quality of work life in the Inside Machine Shop.

B. Goal: Develop and maintain a human resources program to meet future requirements.

C. Objectives:

1. Provide a safe work environment, including prevention of safety deficiencies.

2. Quality of worklife:
   a. Employee involvement, and
   b. Employee recognition.

3. Identify and maintain an adequate training program and skills mix to respond to changing technology (e.g., CNC), modernized systems, varying workload, and workforce demographics:
   a. Apprentice
   b. On the job
   c. Hires,
   d. Skills tracking system,
   e. Supervisory/management, and
   f. TQL.

4. Review, revise and develop position descriptions to meet demands of changing technology.

V. Shop Operations

A. Definition: All industrial processes applied in the manufacture, repair, assembly, and test of ship components assigned to the machine shop.

B. Goal: Continuously improve shop work processes.

C. Objectives:

1. Conduct process flow analyses. This includes development and application of process flow charts, process instructions, and methods and standards.
   a. Benchmark industrial processes to identify the most efficient and effective processes

2. Apply results of parts mix, group technology, and process flow analyses, including:
   a. Development of manufacturing and repair cells, and
   b. Shop floor layout.

3. Apply and integrate manufacturing engineering and process planning.

4. Improve capability and effectiveness of quality assurance and inspection.
   a. Implement an effective Quality Measurement and Tracking (QM&T) system, and
   b. Integrate inspection/ QM&T data with process and machine tool improvement.

5. Improve hazardous material control and waste minimization.

6. Develop and implement procedures for kitting.

7. Evaluate and upgrade scrap metal recovery.

VI. Customer/Supplier Interface Processes

A. Definition: The Inside Machine Shop interfaces as a customer of various information and material suppliers whose actions directly affect shop performance. These suppliers include planning & estimating, supply, scheduling, design, public works, quality assurance, engineering, training, and other shops.

B. Goal: Receive accurate and timely information and material from all suppliers in order to optimize Inside Machine Shop mission effectiveness.

C. Objectives:

1. Develop a work package integrating AIM that provides:

a. Accurate job orders detailing work to be accomplished at the individual task level that reflect the current shop process,

b. Accurate and timely technical requirements and resolutions at the individual task level, and

c. Dynamic work scheduling at the individual task level.

2. Implement a process to identify and procure contingency material to support timely accomplishment of work.

3. Take actions to improve workload leveling and skills retention.

SHOP 31 MODERNIZATION PERFORMANCE MEASURES

Performance indicators were established in order to measure the effectiveness of the modernization initiatives and, more importantly, to provide continuing information and data for the ongoing improvement and modernization of Shop 31 business and operations. These shop performance measures include the information and data required to monitor progress towards the goals established for each of the functional areas. No single measure serves as a complete representation of performance; they all must be reviewed and evaluated in an integrated manner. There are three levels of Shop 31 modernization performance measures.

The first is the macro-level measure to gauge overall Shop 31 performance, which is also used for reporting to headquarters under COSP reporting requirements. This measure is based on available data from the existing naval shipyard cost/schedule control system and reports, and will address both cost and schedule performance.

The second level consists of measures to be applied by all shipyards to assess progress in modernization and improvement more closely correlated to the specific functional areas, goals, and objectives of the Corporate Master Plan. These include the manhour cost per part measured and benchmarked over time for selected representative Shop 31 processes or products (e.g., repair & manufacturing, surface ship & submarine); quality of in-process, final shop, and final ship products based on QM&T system data; the percent of CNC machine tools versus the total number of machine tools in Shop 31; the cost for maintenance (total and corrective and preventive, separately) performed on Shop 31 equipment; post installation economic cost-benefit analysis for all capital investments; reduction of obsolete or excess capital equipment capacity; official safety deficiencies as cited by the shipyard safety office; and productive vs. ancillary vs. non-productive time.

The third level requires that each shipyard develop and implement additional detailed measures to meet their needs within their shipyard plan.

MODERNIZATION INITIATIVES

The following sections provide a brief overview of representative initiatives completed or now being implemented as part of the Naval Shipyard shop 31 Modernization Corporate Master Plan:

Benchmarking

The Shop 31 PAT undertook benchmarking activities to identify the existing and developing state-of-the-art in industrial management and technology systems, in order to move towards the 21st century. Following is a list of completed activities. A partnership was established with the NIST Automated Manufacturing Research Facility (AMRF), which is chartered to assist U.S. industry in advancing technology. Visits were made to organizations with an advanced state of machine shop modernization, such as Watervliet Army Arsenal, Oklahoma

City Air Logistics Center, Naval Ordnance Station Louisville, John Deere, and the South Carolina Research Authority facility. PAT meetings were held at each Naval Shipyard to observe and share the individual shipyard modernization initiatives. A training course in Group Technology and Computer Aided Process Planning was provided to all PAT members. PAT/committee members attended a variety of professional, technical, and equipment conferences and exhibitions. Articles and information from published trade and technical resources were reviewed, including materials from the NSRP. A Navy/industry Best Manufacturing Practices survey was conducted at Charleston Naval Shipyard.

These learning or benchmarking activities enabled the PAT to gain increased awareness, knowledge, and understanding towards the vision of a modern machine shop.

Setup Reduction

The plan includes an objective to reduce equipment setup time, consistent with the Single Minute Exchange of Die (SMED) methodologies developed by Shigeo Shingo. The goal was to maximize equipment productive time "cutting chips" and minimize the product manufacturing/repair cycle time, by reducing equipment setup and changeover time. To assist in this initiative, the PAT enlisted the support of a professor from the Naval Postgraduate School. He visited each naval shipyard to present a setup reduction training course and provide on-site consultation concerning SMED applications in each machine shop, and provided a report of findings and recommendations across all shipyards.

Examples of specific shipyard setup reduction initiatives, which address both internal and external techniques, include the application of modular fixturing, standardized multi-station tool changers, preset tooling, pallet changers, single motion hold-down devices, visual controls, and improved tooling/ fixturing inventory control.

Hazardous Waste Minimization

The imperative for and benefits of hazardous material control and hazardous waste minimization are well known. Environmental compliance and protection, including hazardous waste minimization (HWM), is a key COSP goal and initiative. Although the machine shop is not necessarily a "big ticket" hazardous waste generator in terms of the overall shipyard, a focused Shop 31 HWM study was conducted as part of the modernization program. Elements of the study included: 1) identification of the primary hazardous materials used in machine shop processes; 2) identification and quantification of the primary hazardous waste streams including the generating industrial processes and the waste disposal methods; 3) identification of all completed, underway, and planned HWM projects in each Shop 31; and 4) a survey of external organizations, both industrial and research, to obtain information on machine shop HWM initiatives, including best available demonstrated technologies and management practices. The following are examples of shipyard Shop 31 hazardous material and waste minimization initiatives: improved machine tool coolant management including recycling and use of better coolants (e.g., longer life or increased resistance to rancidity); use of stills for solvent recycling; non- or less-hazardous parts cleaning processes; establishment of a "reutilization store" where useable quantities of otherwise excess hazardous materials are dispensed to other users in order to eliminate illegal storage or loss to shelf life expiration; development of a computerized database system for tracking the purchase, use, and disposal of hazardous materials; a computerized database for determining non- or less-hazardous substitute materials; and designation of shop hazardous materials coordinators responsible for ensuring compliance with policies and regulations.

Capital Equipment

There were several initiatives undertaken in the area of industrial plant equipment, such as development of an effective equipment preventive maintenance program (versus excessive corrective maintenance), disposing of excess equipment, development of standard machine tool specifications, and rebuild and retrofit of existing plant equipment. The primary effort was to evaluate the types and sizes of machine tools that would give the best overall performance, matching future workload requirements with modernization concepts and available technology. Two of the shipyards had completed a thorough parts mix analysis and identified parts families in the projected workload.

Capital investments for plant equipment totaling approximately $65M were made across all naval shipyard machine shops. Following is a list of the representative major industrial plant equipment purchased for Shop 31 modernization: universal turning centers, horizontal boring mills, wire electrostatic discharge machines, vertical boring mills, vertical machining centers, and coordinate measuring machines.

Manufacturing/Repair Cells

The concepts and techniques of establishing work cells are a fundamental element of flexible computer integrated manufacturing/ repair. Product line cells for both manufacturing and repair applications are being implemented in Naval Shipyard machine shops as part of the modernization initiative. Examples of two completed projects are described herein: the Portsmouth Naval Shipyard fastener manufacturing cell, and the Charleston Naval Shipyard Rapid Acquisition of Manufactured Parts (RAMP) Cell.

The fastener manufacturing cell was an applied research and development project with NIST, in collaboration with industry partners. The fastener cell provides an on-line error compensation machining system equipped with the necessary computer control systems for the efficient production of precision threaded fasteners. As an integrated workstation that applies in-process inspection, statistical analysis and process control techniques, it offers a significant reduction in time and money necessary to produce quality fasteners. The cell consists of a UNIX based workstation controller, thread gages, a turning/ milling center with bar-feed capability, a computer aided manufacturing system, and a computer numerically controlled engraver. Programs can be downloaded to the workstation controller via a fiber optic link. In addition, the workstation has hardware and control software to inspect the parts during manufacturing for thread elements such as the cumulative effect of variations in the lead, flank angle, taper, straightness and roundness of the pitch diameter. The control system adjusts the turning/milling center variable and offsets using the error compensation algorithm through DNC to correct for tool wear, thermal growth, pitch diameter, and other machining errors based on probing and thread gaging data obtained during the inspection process. Deburring of the fastener is integrated into the machining process.

The RAMP cell at Charleston Naval Shipyard is an advanced, state-of-the-art flexible cell for the manufacture of small machined parts. It provides a computer driven system for the complete generation, release, scheduling and tracking of shop work orders through eleven computer numerical controlled machine centers. While primarily designed to support rapid manufacture of small lot replacement parts (typical turn around time of less than 30 days), this flexible manufacturing work cell will also support larger fabrication lots. The RAMP computer architecture is comprised of eight integrated top level components operating on four separate computer platforms. The components include modules for site interface, production and inventory control, manufacturing engineering, manufacturing, quality, information management, communications, and an order processing manager. The cell includes workstations for material preparation, tool preset, tooling storage, pre-fixturing for pallet

load machines, and deburring. The system performs on-line inspections of finished products to ensure part quality. Parts can be manufactured from a wide variety of input specifications, ranging from paper drawings to Product Definition Exchange Specification (PDES) files to reverse engineering on "make per sample" parts. The system is capable of paperless manufacturing through the use of PC workstation controllers which provide graphics at the job site for every part to be manufactured, including graphics of the job setup and every tool to be used.

Computer Integrated Systems

In addition to LAN, DNC and AIM systems, other programs have been developed to move towards a flexible computer integrated manufacturing and repair environment.

An automated shop floor control (SFC) system was developed to provide for automated production control, labor tracking, and resource-based scheduling and workloading. SFC is used to create and maintain shop work instructions (SWI), which contain sequenced routing steps for a systematic work process, as well as labor, material, technical reference, testing and quality requirements to the individual SWI route step. The shop floor foreman has on-line SFC access to active SWI information, and is able to personnel and machine resources to each route step. SFC alerts the foreman to resource conflicts. The routing can be electronically modified as needed on the shop floor. This allows the planner or supervisor to add, change, or delete steps in the process as required. Work status data is gathered using bar-code equipment when the mechanic starts and stops each route step. All SFC data is available for reuse on repetitive work and for historical and statistical purposes. A variety of reports are automatically available.

A Factory Floor Integration System for Distributed Numerical Control (FFIS-DNC) has been developed by Norfolk Naval Shipyard with Intergraph Corporation. The primary purpose of this system is to provide a complete electronic support package which will display the information and data required by the shop floor manufacturing technicians such as drawings, process plans, tool lists, setup information, NC tapes, etc. Through a relational information system, FFIS-DNC has a transparent real-time interface to the existing SFC system to allow FFIS-DNC to access shop work information data as well as other scheduling and machine loading data. The mechanic may view all files in the support package at the workstation on the shop floor.

CONCLUSION

The NSRP'S Plan For The Future; The National Shipbuilding Initiative, outlines a comprehensive strategy to ensure continued survival of the U.S. shipbuilding and repair industry. This NSRP initiative includes a major focus on the implementation of technology and know-how that will advance the industry's capability to compete in world markets. The Naval shipyard COSP Shop 31 Modernization Program is implementing management and industrial technologies to propel the inside machine shops into the 21st century, and enable improved performance of the total shipyard mission. The Shop 31 Modernization Corporate Master Plan provides a framework of the attributes to be considered for a comprehensive, structured modernization program in any industrial operation including shipyards. The plan addresses the functional areas of equipment, facilities, integrated management systems, human resources, shop operations, and customer/supplier interface processes. Failure to focus on all areas in a systematic plan, integrated with the total organization's strategic plan, will suboptimize results. Furthermore, in TQL parlance, the plan must be a "living document" and the effort a continuous journey. The bottomline is that these areas must be modernized to achieve fast delivery, high quality, and high productivity, the keys to survival of the U.S. shipbuilding and repair industry.

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Fundamentals of Arc Stud Welding: An Interactive Multimedia Lesson for Shipyard Training

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ABSTRACT

SP-9's 1991 report, "Recommendations on the Use of Interactive Instruction for Training Shipyard Trade Skills," indicates that although very few American shipyards have used it or are familiar with it, interactive multimedia has great potential as a low-cost, effective method for the training of skilled trade tasks. These findings led SP-9 to develop an interactive lesson that demonstrates how interactive multimedia can be integrated into shipyard training programs to reduce training costs, increase productivity, promote quality awareness, and improve worker competence.

The demonstration combines computer graphics, animation, still and motion video, sound, and touchscreen interaction to demonstrate the broad spectrum of the interactive multimedia technology. This paper describes the project as an example of how shipyard training departments can develop their own interactive multimedia courseware by determining appropriate applications of the technology selecting the most suitable hardware and authoring system for delivering the instruction researching, planning and designing the lessons; and shooting the video, authoring the courseware, and integrating them into an effective interactive multimedia course.

INTERACTIVE INSTRUCTION

Interactive multimedia is the result of technology's ability to bring together, in a low-cost computer environment, new forms of visual and auditory stimuli, and allow human operators to interact with them in ways never before possible. Faster yet smaller processors, large capacity desk-top storage, life-like color motion and high-resolution display capabilities, and a variety of new interface technologies produce highly effective exchanges of information between the media and its user. Interactive multimedia has become the platform from which ambitious applications of instructional technology are being launched worldwide.

"Interactive instruction," as the name implies, uses interactive multimedia for education and training. It requires the trainee to become an integral part of the overall educational process. Interactive instruction links an audio/visual presentation to a microcomputer through the use of computer software specifically designed to react to each trainee's individual needs. It establishes a personal relationship between the trainee and the subject matter to& learned. The combination of sight, sound, personal interaction, and computer control provides a highly effective learning environment.

COMPONENTS OF INTERACTIVE INSTRUCTION

The components of interactive instruction are as fluid as the computer industry that produces them. Their functions, however, remain consistent: to stimulate, to evaluate, and to communicate. Technological advancements such as digital video (DVI) and compact disc (CD-I and CD-ROM) do much to enhance the learning environment, and are being rapidly accepted in the instruction role. Interactive videodisc (ND), however, continues as the most popular media for interactive motion video, and it is the platform that is used in this project.

The IVD platform consists of the following six essential components, although others can be added to expand this particular multimedia technology capability.

1. A desk-top personal computer (PC) that initiates all the instructional features, processes and evaluates trainee responses, and provides lesson management.
2. A color monitor for the presentation of visual information from the computer and video player.
3. Interaction devices, such as a touchscreen that signals the computer when and where the screen is touched, and a keyboard for answering questions with numbers or text.

4. A graphics its overlay board with Super VGA capabilities that permtis the combined display of motion video and computer graphics on the monitor.
5. A laser disc player that retrieves video imagery and audio information from a 12-inch optical disc. The retrieved information is controlled by the computer. Videodiscs, unlike video tape, provide the ability to access any portion of a video program instantly. This allows the computer to "branch" to other video segments, skip ahead, or repeat.
6. IVD courseware that manages and administers the training program, and a videodisc that contains the video portion of the lesson.

BENEFITS OF INTERACTIVE INSTRUCTION

Interactive instruction has acquired, and continues to acquire accolades for its achievements in cost-effective training. Industry, government, and the academic community attribute this to the way the multimedia is designed and, equally important, to the way it is applied. Studies (1 and 2) compiled over the past two decades have found that computer-aided instruction significantly reduces training time. This is due to the instructional method of "self-pacing" that directs the most efficient path of learning, the use of auditory cues and narration to reinforce text and pictures, the immediacy of feedback to augment trainee actions, and the computer's "capacity" to adapt to personalized styles to maximize learning efficiency.

The cost of interactive instruction lies mostly in its initial production, not its distribution or use. For this reason, cost-per-trainee is reduced as more trainees use the program. Also important, interactive instruction does not have "bad" days, or tire toward the end of a session. Instruction is delivered consistently and reliably. With interactive instruction, trainees are free to ask questions and explore ideas that might otherwise cause embarrassment. Interactive instruction encourages trainees to persevere and review materials until real mastery is achieved. Unlike traditional training, interactive instruction does not present new material until current material is mastered. This ensures that trainees have strong foundations for continued learning.

Trainees can explore potentially hazardous subjects or dangerous activities without risk to equipment or themselves. In addition, one-to-one interactive instruction focuses the trainee's attention, thereby reducing distraction or disruption. Individual involvement is highly motivating to the trainee and instills a sense of responsibility. The portability of delivery systems can establish a training environment in locations where trainee populations would not otherwise support full-time instructors or where qualified instructors are unavailable. Interactive instruction also makes "any time" training a reality. This is extremely important in a production environment that operates round-the-clock

Trainees who use interactive instruction take greater control and responsibility for their own learning process. As they become more accomplished learners, they become fully active participants in the learning process, not just passive recipients of instruction. As a result, the training "sticks."

Interactive instruction is particularly effective in the shipyard environment where worker proficiency must be proven and documented, and where trainees vary in experience, learning ability, reading ability, or language. The low-cost and portability of the delivery system is a significant benefit where there are many trainees distributed over time or in different locations. Also, the use of multimedia and computer-based training, and the operation of PCs are familiar to most shipyard training personnel.

THE SP-9 PROJECT

The project described in this paper is being sponsored by the Education and Training Panel, SP-9, to demonstrate the benefits of interactive instruction to shipyard management and training department personnel. The project has resulted in an interactive lesson on the "Fundamentals of Arc Stud Welding" to be used by shipyards both to evaluate the training-effectiveness of interactive instruction, and to determine the ease with which interactive courseware can be developed by the shipyards themselves.

Goals of the Project

The specific goals of the project are

1. To demonstrate to shipyard training departments and personnel the use and benefits of interactive instruction for training shipyard skilled trades,
2. To demonstrate how interactive instruction can be used for both tutorial and simulation lessons,
3. To demonstrate to shipyard training departments and personnel the ease and low cost with which interactive instruction courseware can be developed and produced in-house,
4. To provide an interactive lesson on the fundamentals of arc stud welding, and

5. To provide the Shipyard Instructional Design Center and other shipyard training departments with experience in the development of interactive instructional courseware.

Methodology

The Fundamentals of Arc Stud Welding interactive lesson was developed jointly by Ship Analytics, Inc. and NAVSEA'S Shipyard Instructional Design Center (SIDC), Norfolk Naval Shipyard. The lesson was produced using a popular, commercially-available authoring system. This authoring system, and the hardware used to support it, was selected after a thorough review of the various types and capabilities of authoring systems, and the different multimedia technologies associated with interactive instruction. Most favorable for the selected authoring system was its ease of operation, capacity for expansion, relatively low cost, and overall popularity among interactive courseware developers. There are may other authoring systems available that would have been equally acceptable, and many additional ones continue to appear on the market.

The hardware used for the SP-9 demonstration lesson consists of a U.S. manufactured IBM-compatible 80486 computer operating at 25MHz. Computer speed is important when re-drawing interactive multimedia displays. The computer is equipped with Super VGA, a surface acoustic wave touchscreen color monitor, a graphics overlay board for displaying graphics on top of video pictures, and a laser videodisc player. Similar hardware for interactive videodisc systems is available on the commercial market for approximately $7,000. Similar-capability authoring systems are available on the commercial market for less than $2,000. This means that a complete interactive instruction system can be purchased for under $10,000, and can be used in shipyards to develop and teach hundreds of interactive lessons.

The Development Process

Development of the SP-9 interactive lesson followed the traditional process illustrated in Figure 1. This process required the formal publication of "objectives," a "flow diagram," "storyboards" complete with screen text, narration, video and graphics, and a video shot list to guide the video production.

WHY ARC STUD WELDING?

A major objective of the SP-9 lesson is to demonstrate that interactive multimedia is extremely effective at providing both "tutorial" and "simulation" instruction. Since cognitive skills (those requiring mental processing of facts) are best taught through the tutorial process, and stimulus-response (or "trial and error") skills are best taught through simulation; it was decided to select a complex shipyard trade task that would benefit from both types of learning. Portable electric arc stud welding was determined to be such a task.

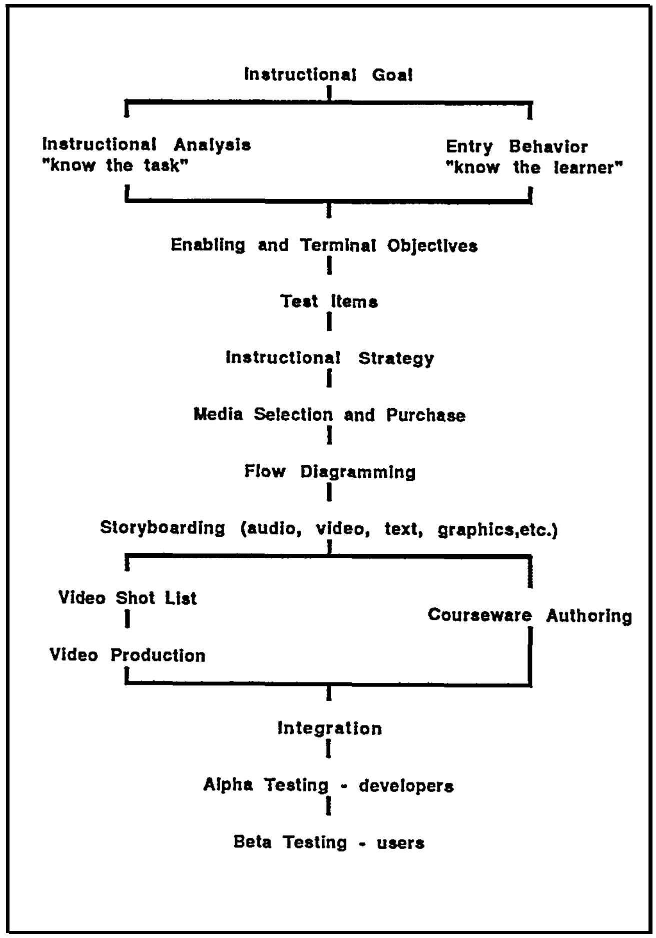

Figure 1 The Interactive Courseware Development Process

Tutorial

Interactive instruction as a tutorial presents the material to be learned in a methodical, progressive manner such that the information imparted to the trainee

is easily understood, easy to remember, and easy to apply. The subject material is usually one that requires competence in recognition and interpretation, knowledge of procedures and processes, ability to analyze and make decisions, and the ability to communicate. Such training is traditionally taught by lecture, reading, and audio/video tape. Interactive instruction, however, adds the elements of motivation and self-pacing through sensory stimulus, physical interaction, continuous testing, feedback, and branching.

Simulation

The other effective use of interactive instruction is practicing skills and rehearsing complex procedures through simulation. Training a skill such as arc stud welding, that requires extensive trial and error coordination and the rehearsal of procedures for gun adjustment and inspection of welds, is an excellent application of simulation. For this application, pictures of actual equipment are shown. The trainee can touch the picture to simulate handling or adjusting equipment, and the picture changes in response to the action. The trainee is thereby guided through both set-up and operating tasks, and can experience the consequences of his or her actions. The trainee can also practice procedures over and over before being tested.

Of particular importance is the cost savings realized by having the trainee learn procedures and practice skills without using actual equipment. Interactive instruction eliminates the need to take equipment out of service for training purposes, and significantly reduces the risk of injury to personnel or damage to equipment.

THE LESSON

The interactive lesson uses text, graphics, animation, photographs, still and motion video, and sound to stimulate learning. It uses a touchscreen to accept trainee responses, and it illustrates self-pacing through a variety of different types of remediation and feedback loops. Trainees are automatically screened with a pre-test just as they would be in traditional training, and their performance is verified and documented at the end of each lesson. Answer analysis and student management, routinely conducted during training, are also performed by the system.

One additional objective of the lesson is to illustrate different presentation and feedback techniques that are available through interactive instruction. The lesson carefully balances this objective with the requirement of a good interactive lesson which is to maintain consistency throughout.

Lesson Modules

The "Fundamentals of Arc Stud Welding" consists of the following modules:

Module I - Initialization
Module 1 - About the Lesson
Module 2 - Theory
Module 3 - Studs and Ferrules
Module 4 - Welding Equipment
Module 5 - Welding Procedures
Module 6 - Inspections and Tests
Module 7 - Practice
Module 8 - Examination

These modules are arranged within the structure of the lesson such that all modules are administered to new trainees, while individual modules can be randomly accessed by experienced trainees who are receiving refresher or re-qualification training. Figure 2 illustrates the interaction of these modules.

Feedback

The form and timing of feedback to the trainee is the heart of interactive instruction. This feedback results from the trainee's response to a question or required action, and provides the immediate re-enforcemement so vital to the learning process. Many forms of feedback maybe used in an interactive lesson. Most authoring systems contain provisions for automatic feedback. Figure 3 illustrates some of the feedback loops used in the current project.

GETTING STARTED

Learning from interactive multimedia is an experience not to be missed. From the very start, its sights and sounds provide a continuous challenge, requiring the trainee to identify components by touching them to make simulated equipment adjustments and to answer questions.

The complete arc stud welding lesson covers theory, workstation set-up, operation of equipment, inspection of welds, and practice. Duration of the lesson depends upon the trainee. If all branches are viewed, the lesson will last approximately one hour. It is possible for a fast learner to take the entire lesson in less than half that time. This is one of the strengths of interactive instruction.

Upon being seated at the interactive workstation, a trainee begins by typing his or her name into the lesson management data base. This ensures that the trainee is approved for the course, and a file for

recording the trainee's progress is created. By touching the screen, the trainee is guided through a series of still and motion videos, animation, graphics, text, and narrations. Each module contains questions that must be answered. The lesson makes extensive use of simulation to describe procedures and encourage practice. Some questions require either a "point-to" or "button-Press" response from the trainee. The accuracy of these responses is used to determine whether the trainee should receive additional instruction; and, if so, what type of remediation it should be. If warranted the trainee receives a special remedial branch, or in some cases the original presentation is simply repeated. In all cases, the responses of the trainee are used to determine whether the lesson was completed satisfactorily. The end result is that the trainee becomes aware of his or her own capabilities, and management receives assurance that safe, cost-effective arc stud welding will be performed.

WHAT IS EXPERIENCED ALONG THE WAY

Fundamentals of Arc Stud Welding contains more than 200 "units," which is the authoring system's term for unique frames or screens. This means a slow learner has that many opportunities to receive

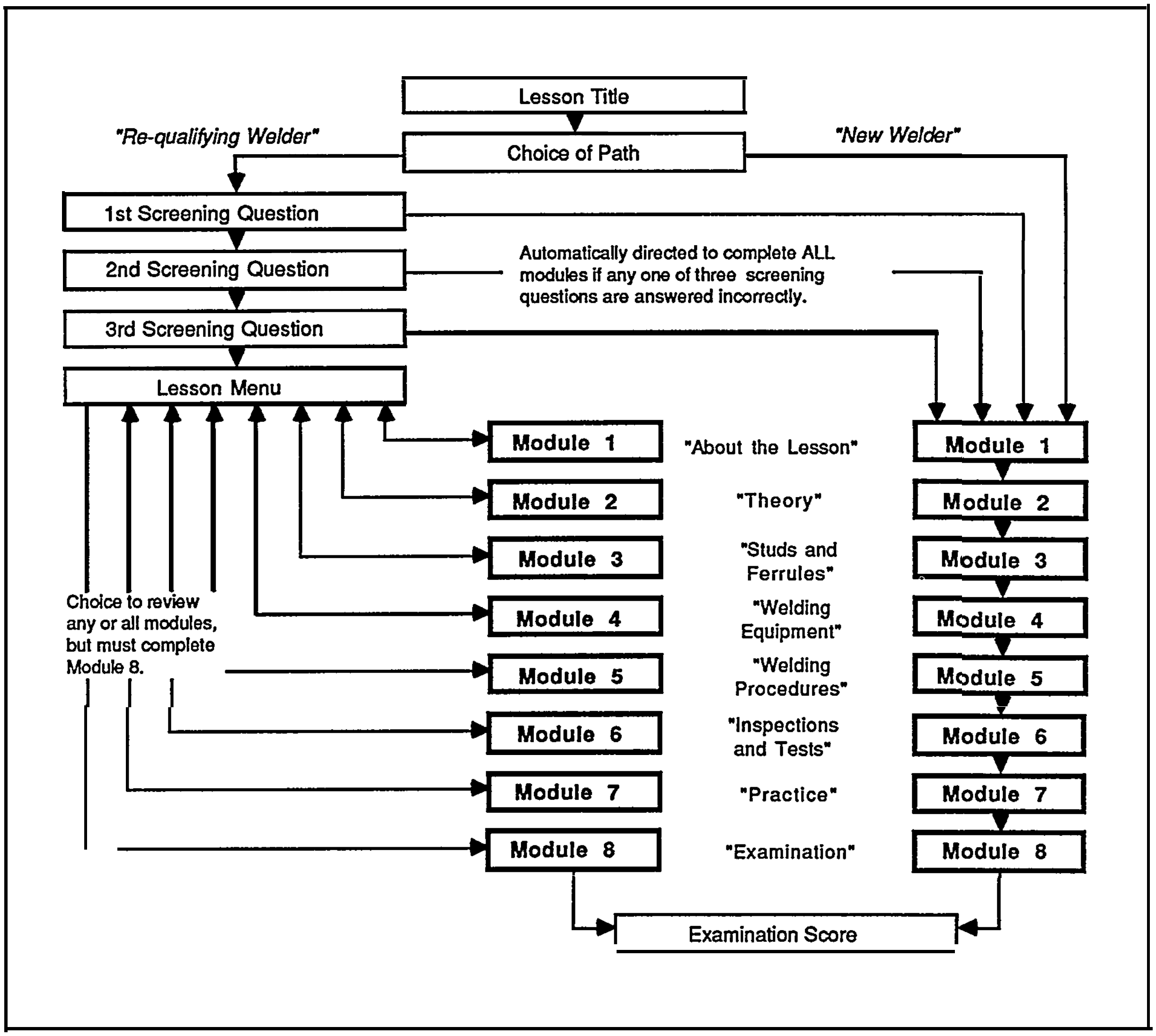

Figure 2 Modules of the Arc Stud Welding Lesson

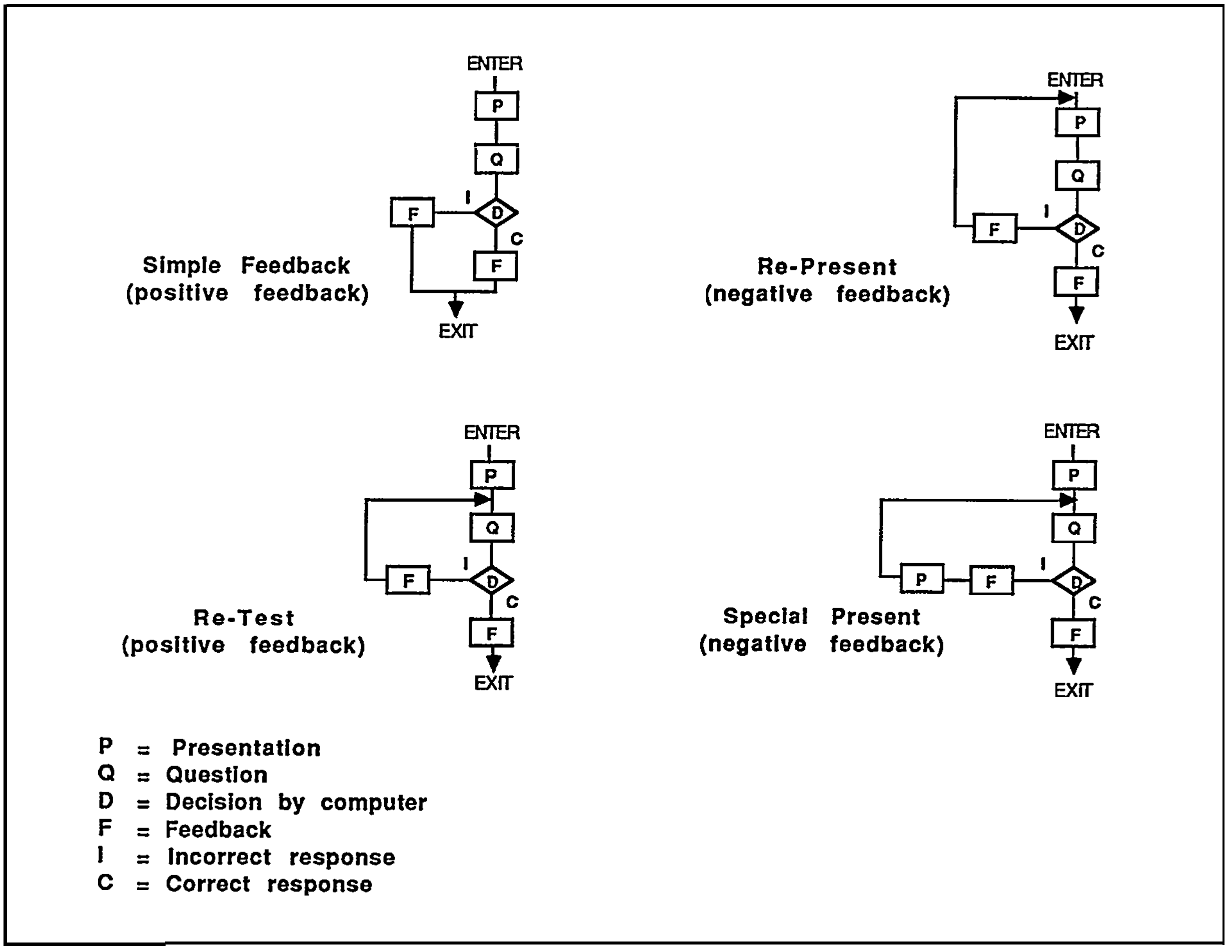

Figure 3 Examples of Inter-Module Feedback and Branching

information. The fastest learner will receive the same knowledge from significantly fewer units. The large number of units represents the opportunity to demonstrate many different instruction techniques, while making this objective of the project transparent to the trainee.

The lesson applies human factors engineering design criteria, which include simplicity of format, limiting the variety of color in text, attention to font and character size, maximizing the use of sound and motion, and avoiding unnecessary trainee interaction. The first module provides a brief description of how to operate the lesson. This knowledge is subtly expanded throughout the lesson so that the trainee can eventually perform relatively complex interactions.

A wide variety of feedback techniques are also demonstrated. Most authoring systems provide simple feedback capabilities within individual units, or the ability to branch to other units for more complex feedback. Feedback and branching are the basic ingredients of interactive instruction, and are well demonstrated by the project.

Interaction within a lesson is carried out predominantly by touching the screen. Trainees are asked to touch text panels, buttons, items in a picture or graphic, and, in some cases, "anywhere on the screen." It is accepted that the the touchscreen will be easier than a keyboard or mouse for stud welding trainees to use. There are, nevertheless, some interactions that require simple keyboard entries. These are included to demonstrate such interaction, and careful instructions are provided to guide the trainee in their use.

The presentation of information in the Fundamentals of Are Stud Welding lesson is intended to motivate and educate, while at the same time demonstrate flexibility in interactive screen design. A

variety of techniques for combining video and text are presented. Two unique opportunities for skill practice are provided through simulation. The first simulation presents the colored "flashes" of an electric arc along with its sound, and asks the trainee to identify the "best weld." While it can be argued that these cues are of limited value to a stud welder during actual practice, it does demonstrate how interactive multimedia can be used for sensory stimulation and basic perception tasks.

The second simulation presents pictures of welded studs with varying degrees of defects and nonconformity. The trainee is required to identify what adjustments should be made to the equipment to improve the weld, and then is shown, through a subsequent picture, the results of this adjustment. The simulation permits the trainee to make adjustments to the arc stud welding system, and to experience the consequences of this adjustment. This simulation is provided immediately before the final examination, and only after all other lesson material has been learned.

Motivation and verification are "built-in" to all aspects of the lesson. The trainee is constantly motivated through positive and negative feedback statements, both spoken and printed. Humor, a motivational technique applicable to some subjects, is limited. The lesson is structured to continuously challenge the trainee through the use of rewards and critiques. Both positive and negative feedback are included in the lesson.

FINISHING UP

At the end of the Fundamentals of Arc Stud Welding lesson the trainee is administered ten questions, each with only one correct response, that must be answered within a defined period of time. Although response time can also be used to test trainee reaction time, in this lesson the time element is used only to ensure that the lesson proceeds to the end. The method of trainee response is unique for each examination question. This enables the lesson to demonstrate ten different response techniques: specifically multiple-choice buttons, multiple-choice text, multiple-choice pictures, alternate-choice true/false or yes/no, pointing in a graphic, pointing in a picture, pointing in a video, numeric keyboard entry, text keyboard entry, and press-a-key. Questions are weighted differently in their contribution to the final score.

After the final question, all trainees are congratulated and invited to view their final score, which is derived from question criticality and other data. The instructor receives a full performance report, including a description of which questions were answered incorrectly.

TO DATE

To date, "Fundamentals of Arc Stud Welding" has been viewed only by project personnel involved in its development. The major test of this interactive lesson will come during the next year and beyond when shipyard management and training departments begin to use it, evaluate its benefits, and possibly develop some similar lessons on their own.

Results of the earlier NSRP report, “Recommendations on the Use of Interactive Instruction for Training Shipyard Trade Skills" (NSRP 0334/UMTRI 82210), revealed that while most American shipyards are not completely familiar with interactive instruction, most would be willing to participate in its demonstration. This interactive lesson provides that demonstration. It is intended that the lesson will enable American shipyards to better understand what interactive multimedia is, how the shipbuilding industry can benefit from it, and how interactive instruction can contribute to higher quality, cost-effective production in an ever-increasing competitive market.

REFERENCES

1. Fletcher, J.D., Effectiveness and Cost of Interactive Videodisc Instruction in Defense Training and Education, IDA Paper P-2372, Institute for Defense Analyses, Alexandria, VA. 1990.

2. Orlansky, J. and J. String, Cost Effectiveness of Computer-Based Instruction in Military Training, IDA Paper P-1375, Institute for Defense Analyses, Alexandria, VA. 1977.

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Network Scheduling Development in an MRP II Environment

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ABSTRACT

Large manufacturing industries have been able to successfully reduce cost and cycle time through the use of Manufacturing Resource Planning (MRP II) systems and principles to control material flow and the production process. Ship construction can not be neatly classified as a manufacturing process. The complex relationships involved with the installation and activation of ship's systems more closely resembles a construction operation. Work of this type has traditionally been controlled through an activity based network scheduling system. However, MRP 11 principles offer numerous benefits for the shipbuilding industry. This paper discusses an approach to planning, scheduling, and management of ship construction which takes advantage of benefits from both approaches. By using both network scheduling and MRP II in an integrated scheduling system, a shipyard will be better able to plan and execute the ship construction process.

OBJECTIVE

An effective planning and control process for a shipyard will meet the objectives stated below

- To the greatest extent possible, provide a consistent work approach (common strategy) to take advantage of the learning process,
- Increase producibility by increasing the interaction between engineering and planning functions early on in the design process,
- Provide clear, consistent requirements to materials, engineering, and production departments, reflecting the shipbuilding strategy,
- Provide an accurate and concise analysis of project status to help determine what actions need to be taken to support the ship's completion milestones,
- Provide straightforward impact analysis and rescheduling as deviations from the initial plan occur,
- Provide tools for credible shop floor control which reflect the build strategy, and
- Provide feedback and monitor performance.

With these objectives in mind, an effective method **for scheduling production in a shipyard environment** will be presented.

OVERVIEW

To meet the stated objectives, project planning and scheduling should take a top down approach, starting with general goals and objectives and working towards progressively more detail. As this greater level of detail is developed, it must support the goals and objectives upon which it is based. Taking this top down approach will allow for a more consistent approach throughout the production process. Goals and objectives developed early in the ship design/construction process provide a common basis to which all groups can work. This common basis makes it easier for production, planning, and engineering to work together in developing producible designs and effective build strategies.

The two scheduling approaches most commonly used today are the network schedule and Manufacturing Resource Planning (MRP II). Both approaches present a strategy in the form of a plan. A plan is a simulation of what is needed to reach a goal (e.g. deliver a ship). Each approach has benefits.

The network approach permits better scheduling and control of key events. A network will show the various relationships activities have with one another.

These relationships make the network an excellent tool for assessing the impact of change and reporting activity status. MRP II provides automated schedule generation to the extent that the product structure is defined. MRP II uses a closed loop that provides control over execution of the plan and feedback as events occur to monitor performance.

Design-to-order project shops and construction operations have traditionally been controlled through an activity-based network scheduling system. Mass production manufacturing operations have been able to successfully reduce costs and cycle time through the use of MRP II to control material flow and the production process. The shipbuilding process can not be neatly classified as either a project type construction operation or a manufacturing operation. Shipbuilding contains elements of each. Fabrication of the many components that make up the ship (e.g. piping, vent, machinery foundations) may be viewed as a manufacturing process. Joining of the hull and the installation and activation of the ship's systems more closely resembles a construction operation.

The solution to the dilemma of which scheduling approach to use is a simple one: use both. In this way, the shipbuilding process may take advantage of benefits from both a network and an MRP II scheduling approach.

High-level schedules are developed via a network. The network consists of interrelated tasks that are defined at the appropriate level to drive demand in the MRP II system. Detailed definition of individual tasks is not a network but a materials-based MRP II plan for that master schedule item.

By using a network to drive the master schedule items of an MRP II system, the benefits of both approaches are realized. The network controls the key events, reports status at a high level, assesses the impact of change, and allows for effective rescheduling as deviation occurs. The MRP II system serves as the tool that controls shop floor execution of the plan. The MRP II system provides feedback as events occur in order to monitor performance. The question now becomes: to maximize the benefits of both network and MRP II scheduling approaches, at what level does one define the network which will serve as the top of the MRP II bill? The remainder of this paper will address the development of network schedules and how they are used to drive an MRP II system.

GLOSSARY

The following definitions are provided to clarify usage within this paper. They are not meant to imply an industry standard.

UNIT: A structural assembly which is outfitted and erected on a ship or joined with other units and then erected on a ship.

MAKE-UPS: Small sections of pipe and vent that cross erection butts of units and therefore cannot be installed until the unit is joined to a ship's structure.

BLUE-SKY ITEM: Machinery and material that is loaded into a ship before the unit closing out clear access is erected. This is illustrated in Figure 1.

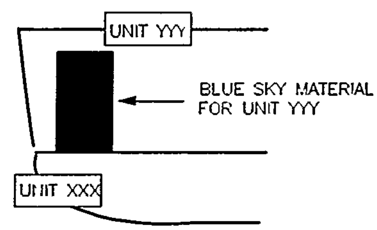


Figure 1: Blue-sky item definiton.

GEOGRAPHIC ZONE: A geographic volume on-board a ship&compassing a logical grouping of work such as a tank or cargo hold.

FUNCTIONAL ZONE: A logical grouping of work on-board a ship that may pass through several geographic zones such as a main cable pull or shafting system.

SCHEDULE DEVELOPMENT METHODOLOGY

In an MRP II system, demand is driven by items at the top of the bill of material. These are the MRP II master schedule items. Defining the master schedule item as the completed ship and structuring the entire build process beneath this activity is not a practical or effective solution. Intermediate milestones would be difficult to evaluate, progress would be difficult to track, and the impact of delays and change would be difficult to assess. The ship

production process should instead be broken down into interim products, which in turn can be broken down into a series of activities or tasks. The tasks required to create the interim products are used as the MRP II master schedule item. All material required to build the vessel is structured beneath the appropriate master schedule item. For shipbuilding, the interim products may be divided into two categories: ground assembly and outfit (GA&O) master schedule items, and on-board master schedule items.

GA&O encompasses steel fabrication, assembly, joining, and erection of units along with shop fabrication and installation of items which are installed prior to erection, and any testing performed prior to erection. On-board master schedule items include the fabrication and installation of make-ups and blue-sky items, as well as remaining work and tests performed on-board the ship.

Definition and scheduling of the activities which comprise the top of the MRP II bills is part of a sequential planning activity process. The planning process is a top-down approach starting at a high "conceptual" level with major milestones and production goals based upon these milestones. These milestones and production goals are used as a basis to develop GA&O and on-board build strategies. The strategies, along with the erection schedule, ship's completion schedule, and process lane strategies are the basis for the development of master schedule networks. These networks drive the MRP II system. An overview of planning and scheduling document development is shown in Figure 2.

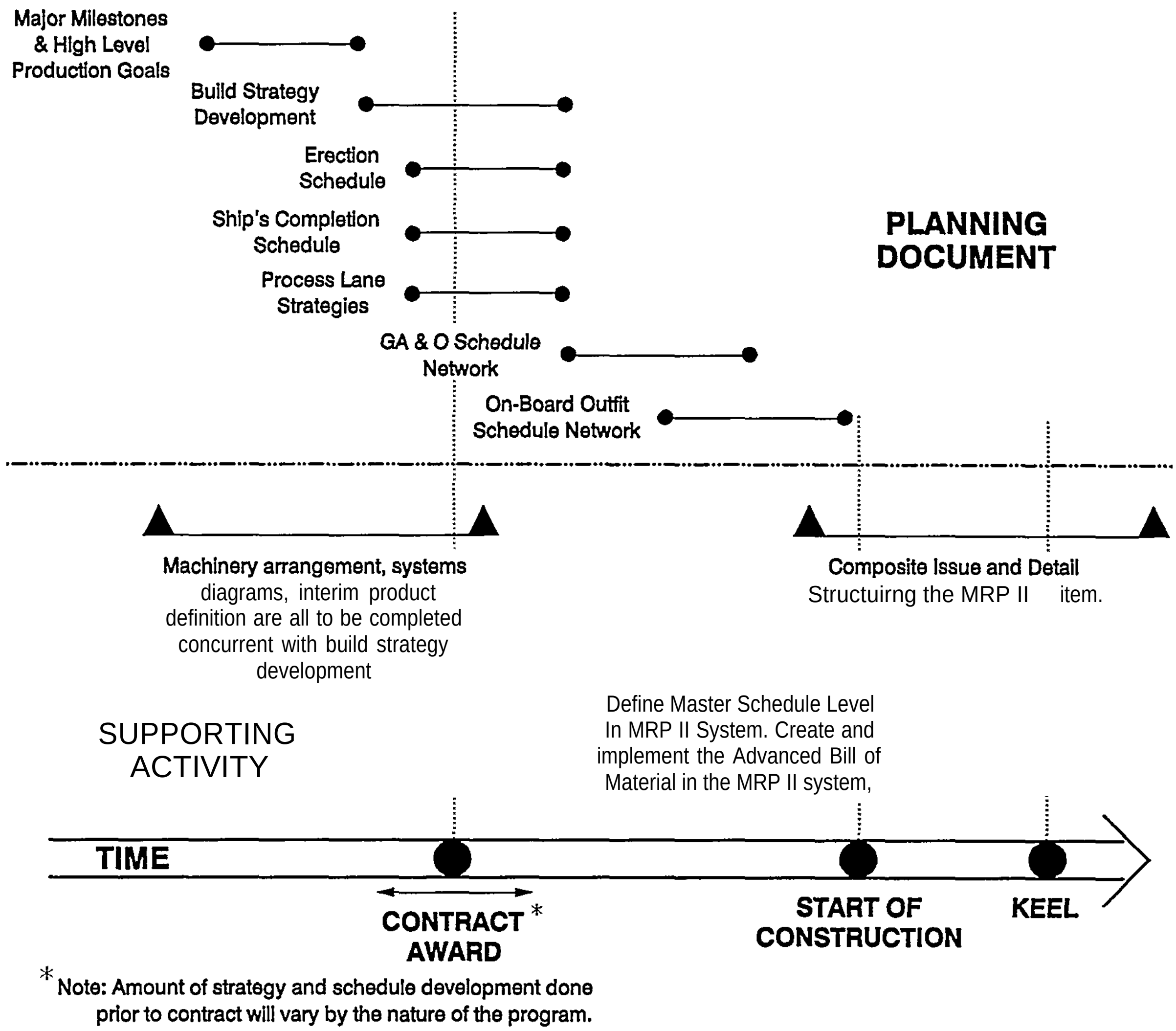


Figure 2 Planning activity timeline when planning and scheduling documents are to be developed relative to key milestones and supporting activities.

HIGH LEVEL STRATEGIES AND SCHEDULES

Major milestone schedules and high level production goals must be developed and agreed to by all concerned groups before further planning can proceed. Major milestone schedules define key events such as contract award, start of construction, keel, launch, trials, and delivery. The schedule is based upon key business plans, contract requirements, and factors such as expected yard manning and workload. High level production goals address the amount of work to be done on the ground and the amount performed on-board. The goals also show when certain parta of the ship are to be built relative to the major milestones. A sample of production goals for a cargo vessel is shown in Table I.

PRODUCTION GOALS						
	GROUND ASSEMBLY & OUTFIT			ON-BOARD		
	ASSEMBLY AREA	MACHRY UNITIZATION AREA	PRE-OUTFIT AREA	COMPL BY STERN RELEASE	COMPL BY LAUNCH	POST IAUNCH
MACHRY SPACES	Innerbottom piping, menholes end ladders compl.	Machinery cores (includlng all equip except ME) complete, hydrood, and flushed.	Sea chests complete	Cores Iand X wks prior to release, install make-ups and remove temp. staging. core make-up compl X wks after relesae.	Power & automation compl, ME connect make-up X wks after launch. Mske-ups w/caslng compl X wks after launch.	Turn over ME X wks after launch
CARGO DECKS	Beck-up structure for deck equip and foundations Installed.	Pipe tacks including machry, valves, elec, air,fire & foam. Piping hydrood, flushed and legged.	Fully outfitted except for make-up pieces at block breaks. Install submerged pumps.	Mske-ups between aft tanks complete within X wks after release.	Make-ups between fwd tanks complete within X wks aftar launch. Submerged pumps Installed.	Deck outfit compl X wks after launch.
DECK HOUSE	Large dla piping, fnds, vent spools and curtain plates.	Fen mom units complete, hydroed, and flushed.	Outfit compl except for mske-up to machinery space.	—	Distibution systems compl, equipment hooked-up, Joiner work compl. X wks after launch.	Flooring, paint end finish work compl X wks after launch.
CARGO & BALLAST TANKS	Outfit compl except submerged pumps and vent Iadders.		Install valve operator reach rods.	—	Cargo and ballast system complete.	Tank outfit compl X wks after launch.
STERN	Tank piping including stem tube LO, ladders, end rnenholes.	Steering gear unit complete, hydroed and flushed.	Mooring equip and fittings install. Hot work on deck compl. Ruddertrunk bored,	Compl stem tube within X wks after release.	Final align shaft and installation compl X wks after launch.	Aft deck outfit complete X wks after launch.
BOW	Belfast piping, ladders, menholes installed.	—	Fwd stores and paint locker compl. All deck outfit including mooring and anchor handling compl.	[redacted]	Make-up to distribution system an deck complete X wks after launch	Fwd deck outfit complete X wks after launch.

Table 1: Production goals for a sample cargo vessel to be used as a basis for more detailed schedule development.

Upon approval of the major milestones and production goals, build strategies are developed for both the GA&O and on-board areas. For GA&O, a vessel is divided into a series of units that allow for efficient erection and the maximum extent of pre-outfit given a yard's facility constraints. Once the u'nits have been defined, strategy sheets may be developed based upon machinery arrangements, system diagrams, right-of-way strategies, and production goals. A good high level strategy may be developed before composite drawings are issued. The sheets describe which items are to be installed and tested at each task within the GA&O process. A sample strategy sheet format is shown in Table II.

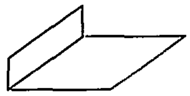
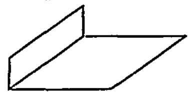
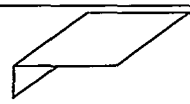
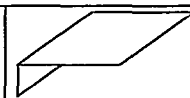
INTEGRATED ASSEMBLY/ OUTFIT STRAT BY UNIT TYPE				UNIT TYPE: CARGO HOLD	
					
TASK / PRODUCT TYPE	ASSEMBLY	PRE-BLAST INVERTED OUTFIT	PRE-BLAST UPRIGHT OUTFIT	BLAST & PAINT	POST-BLAST OUTFIT
STEEL	All structure and related items except for topside work.		Weld-out topside seam.		
PIPE & MACHINERY	Drain wells. Deck penetrations.	Sprinkler piping.			Fire station sensor tubing.
VENTILATION	Vent spools.	Spiral duct.			Cable actuators and pull cables.
ELECTRICAL	Light standoffs. Waterway collars.	Cable ways.	Connection boxes.		Lights, sound powered telephones, local cable.
METAL OUTFIT		Overhead storage rack tracks.	Elevator door stowage. Truck gaurds.		
BLAST & PAINT		Paint in-way-of.	Paint in-way-of.	Sandblast & paint unit.	
PRODUCTION SERVICES		Layout and shoot insulation pins.			Install scaffold for use on-board.
SUB-CONTRACTOR					Insulate.
TEST		Sprinkler local hydro.			

Table II: Ground assembly and outfit strategy sheet for a cargo hold unit.

For on-board, a vessel is divided into geographic and fictional zones which allow for the logical grouping of tasks. Once these zones are defined, on-board strategy sheets are developed. These strategies encompass the remaining work that was not defined by the GA&O strategy sheeta. On-board strategies are developed in conjunction with the GA&O strategies to guarantee that work is assigned to meet the high level production goals. A sample on-board strategy sheet is shown in Table III.

ON-BOARD STRATEGY BY ZONE TYPE					ZONE TYPE: CARGO HOLD		
TASK / PRODUCT TYPE	MAKE-UP FNDS & HOT WORK BY UNIT	STORAGE RACK TRACK INSTALL ON DECK	DECK COVERING	ELEC LOCAL PULL AND HOOK-UP	PICK-UP PIPE VENT, TEST	PAINT-OUT ZONE	Z PHASE ZONE
STEEL					Air test access trunk.		
PIPE & MACHINERY	Make-up pieces. Reach reds.						Sensor tubing.
VENTILATION	Make-up pieces. Thermo bulbs. Vent plenums.						
ELECTRICAL				Pull remaining local cable. Hook-up main and load cable.			
METAL OUTFIT	Waterway coamings.	Complete lower door track. install deck tracks.	install clips.				
BLAST & PAINT	Paint IWO exclusion plates end *vent*	Final paint sumps and close.	Paint IWO deck severing.			FM paint *zone.*	Touch-up final paint
PRODUCTION SERVICES							Remove temp services.
SUB - CONTRACTOR	Insulate IWO as required.		Pour deck covering				
TEST		Check point track allignment					

Table III: On-board strategy sheet for a cargo hold zone,

The erection schedule defines the dates on which units are erected on a ship. This schedule addresses not only steel concerns such as reasonable erection rates which support available manpower and structural integrity, but also outfitting concerns such as loading and installation of major equipment, stem release, and the schedule's ability to support the ship's completion milestones. A sample of an erection schedule is shown in Figure 3.

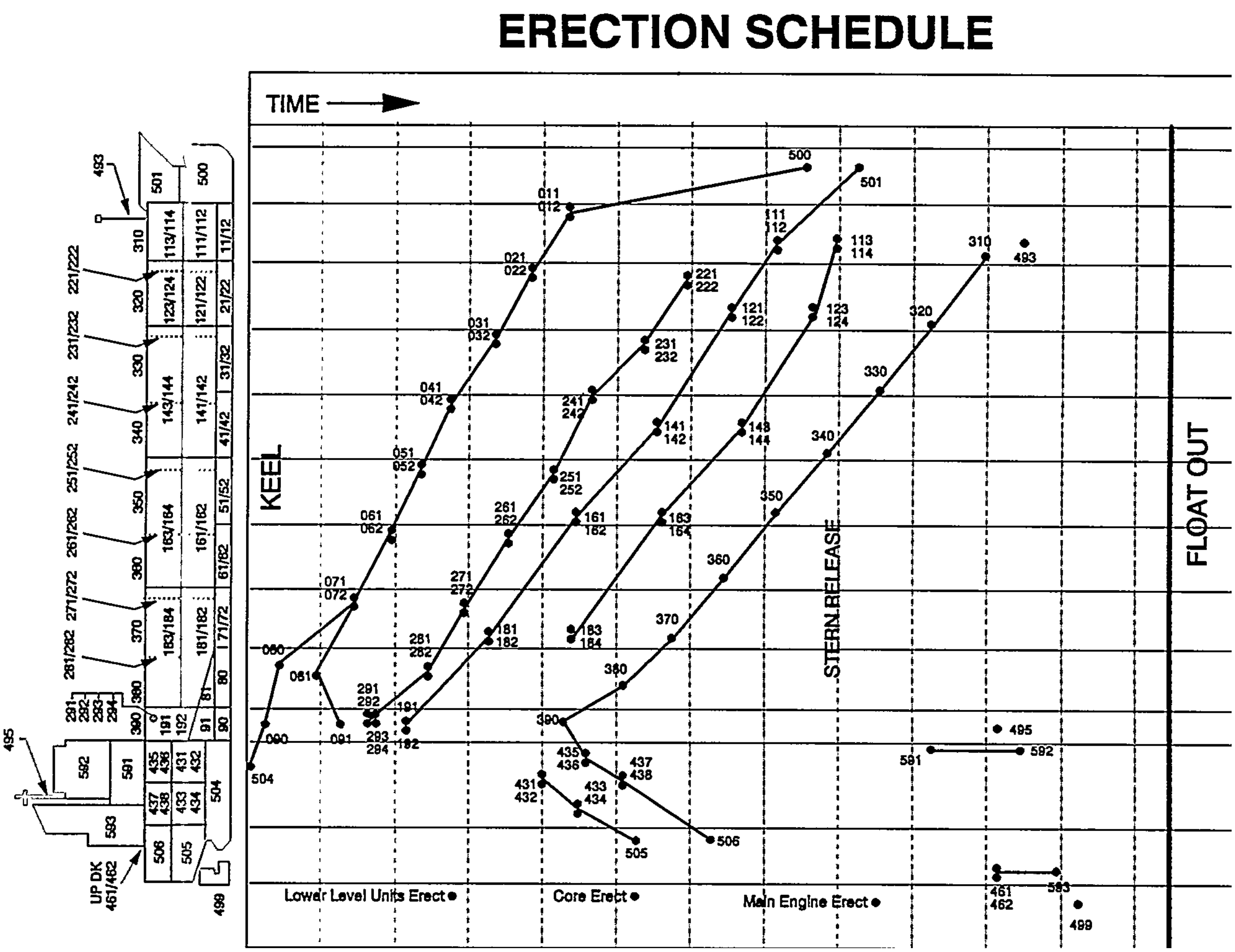


Figure 3: Erection schedule for a sampe cargo vessel defining the dates units are erected to the ship.

The ship's completion schedule defines the dates that high level activities, which are key points in the ship construction process, occur. The completion schedule consists of three types of activities:

- Area close-outs such as forward tanks closed, cargo spaces closed,
- Key events such as stern release, launch, light-Off SSDG'S, and
- Major system tests/trials such as integrated plant testing, sea trials.

A sample ship's completion schedule is shown in Table lV.

Process lane strategies define repetitive work stations in the GA&O area. If multiple items are going to be sequenced through a single location, the second item cannot be started until the first item is complete. Virtual process lanes may be established on-board. A virtual process lane consists of a dedicated work team assigned to do one task in several areas throughout the ship such as the installation of all tank level indicators. Since there is only one team, the tank level indicators in one area cannot be installed until the task has been completed in the previous area. These strategies must be defined so that the proper relationships may be established in the master schedule netvorks. A sample of a process lane strategy is shown in Figure 4.

SHIP'S COMPLETION SCHEDULE

MILESTONE ACTTIVITY		COMPLETION
AREA CLOSE OUTS -	FO Storage/Slop	Launch - X wks
	Ballast tanks, Holds 2-8	Launch - X wks
	ForepeakTank	Launch - X wks
	Casing/Stack	Launch - X wks
	Main/B/C Decks	Launch - X wks
	Bridge	launch - X wks
	Bow(anchor handling, chain Ikr, stores)	Launch - X wire
	Stern(deck machinery)	Launch - X wks
	Machinery Spaces	Delivery - X wire
KEY EVENTS -	Soc	SOC + X wks
	Keel	Keel + X wire
	Stern Release	Keel + X wire
	Launch	Launch - X wire
	Epoxy Stern Tube	Launch - X wks
	Ballast Sys Aft of Forepeak Compl	Launch + X wire
	ME Connection Made-up, Engine Chocked	Launch + X wks
	Make-Up to Casing Compl	Launch + X wks
	Deckhouse Distrib Systems Compl	Launch + X wire
	Final Align Shaft	Dock Trials - X wks
	ME Light Off	Dock Trials - X wks
	SSDG Light Off	Dock Trials - X wire
	Restore Switchboard	
MAJOR SYTEM TEST/TRIALS -	Builders Trials	Delivery -X wire
	Dock Trials	Builders Trials - X wks
	integrated Plant Testing	DockTrials - X wks
	Main Engine Tact	Dock Trials - X wire
	Main Engine Aux. System Test	Dock Trials - X wks
	Generator Load Test/Parallel Test	Dock Trials - X wire
	SSDG Aux System Test	Dock Trials - X wire

Table IV: Ship's completion schedule for a sample cargo vessel,

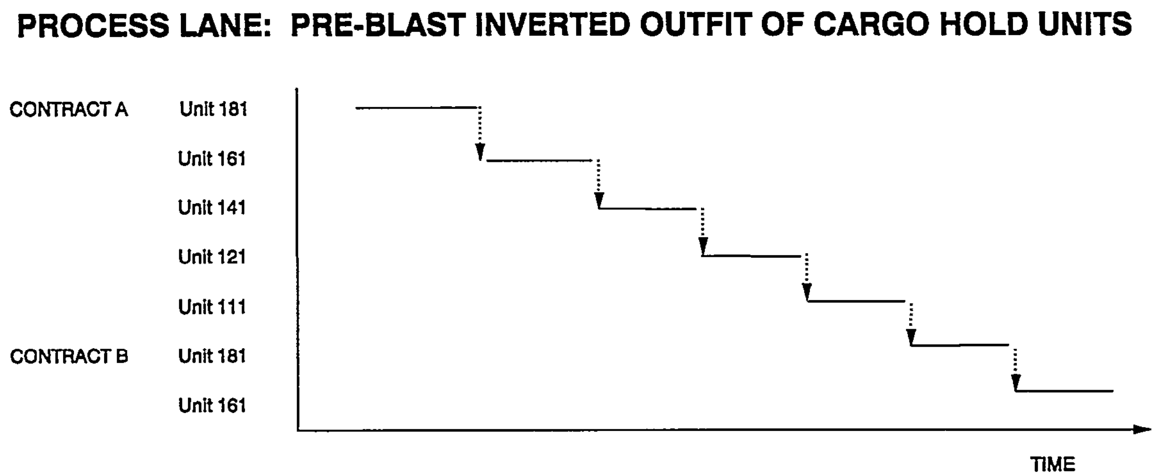


Figure 4 Process lane strategy sheet for pre-blast inverted outfit of cargo hold units.

GA&O MASTER SCHEDULE ACTIVITY NETWORK

The MRP II master schedule items for ground assembly and outfit are defined at the unit task level as shown on the GA&O strategy sheets. These items are the activities which define the master schedule network. The activities modeled by the netvork include assembly of units along with major sub-assemblies. Pre-outfitting may be modeled as a single or multiple activity depending upon the complexity of the unit. Unit erections (as taken from the erection schedule) serve as back-end constraints for the GA&O master schedule activity network. The network defines intra-unit relationships from one activity to another. The network also defines inter-unit relationships as defined by the process lane strategies. A portion of the master schedule network defining a typical unit is shown in Figure 5.

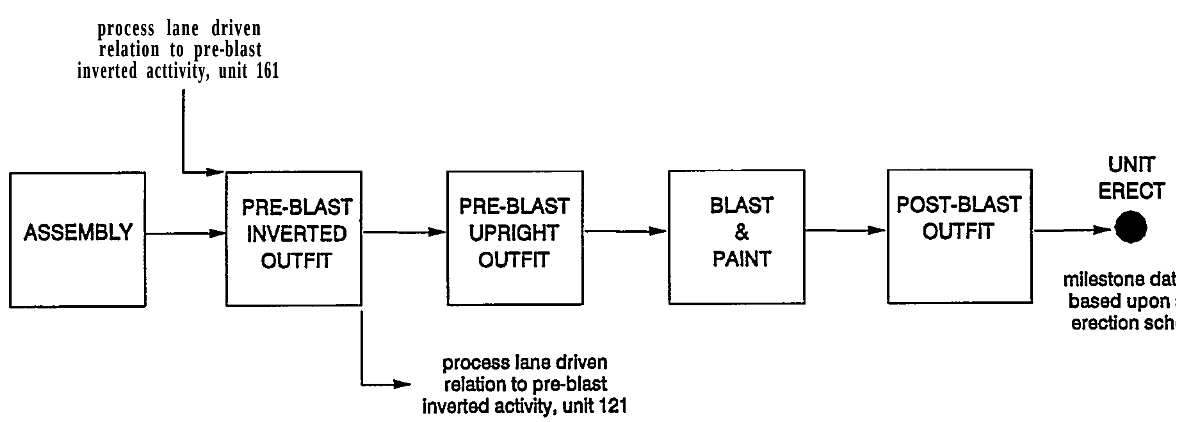


Figure 5 Ground assembly and outfit master schedule network of cargo hold unit 141 based upon the GA&O strategy sheet shown in Table II, and the process lane strategy sheet shown in Figure **4.**

ON-BOARD MASTER SCHEDULE ACTIVITY NETWORK

The MRP II master schedule items for on-board work are defined at the geographic/functional zone task levels, as shown on the on-board strategy sheets. These items are the activities which define the master schedule network. Work defined by the network picks up where the GA&O network leaves off and carries through to completion. The front-end constraints of this network are the unit erections as defined by the erection schedule. The back-end of the network is constrained by the events defined in the ship's completion schedule. The network defines intra-zone relatioosbips as well as the inter-zone relationships between tasks of different zones. A portion of the master schedule network defining a typical zone is shown in Figure 6.

MRP II SYSTEM STRUCTURING

As stated earlier, the activities defined in the master schedule networks are the master schedule parts which reside at the top of MIW II's production bill. All installation and fabrication are structured beneath the master schedule part in MRP II. Definition of these master schedule parts can be done based upon machinery arrangements, systems diagrams and right of way strategies. Detailed structuring of material installation and fabrication beneath these items is done based upon the composite drawings. Structuring for a typical unit is shown in Figure 7 and for a typical zone is shown in Figure 8.

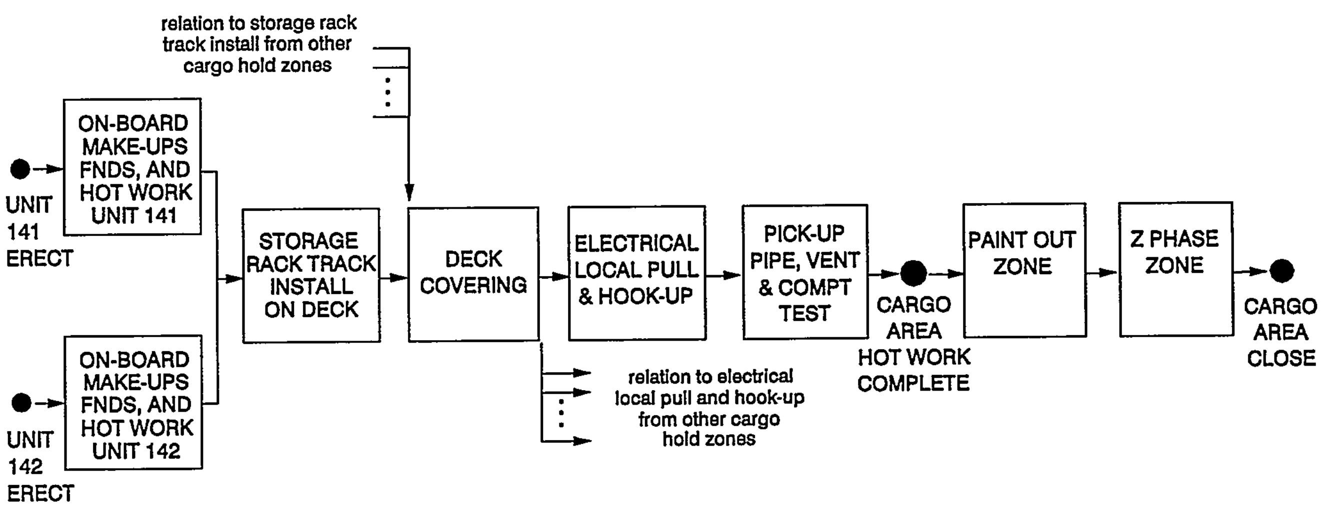


Figure 6: On-board master schedule network of cargo hold zone 1233 based on the on-board strategy sheet shown in Table III.

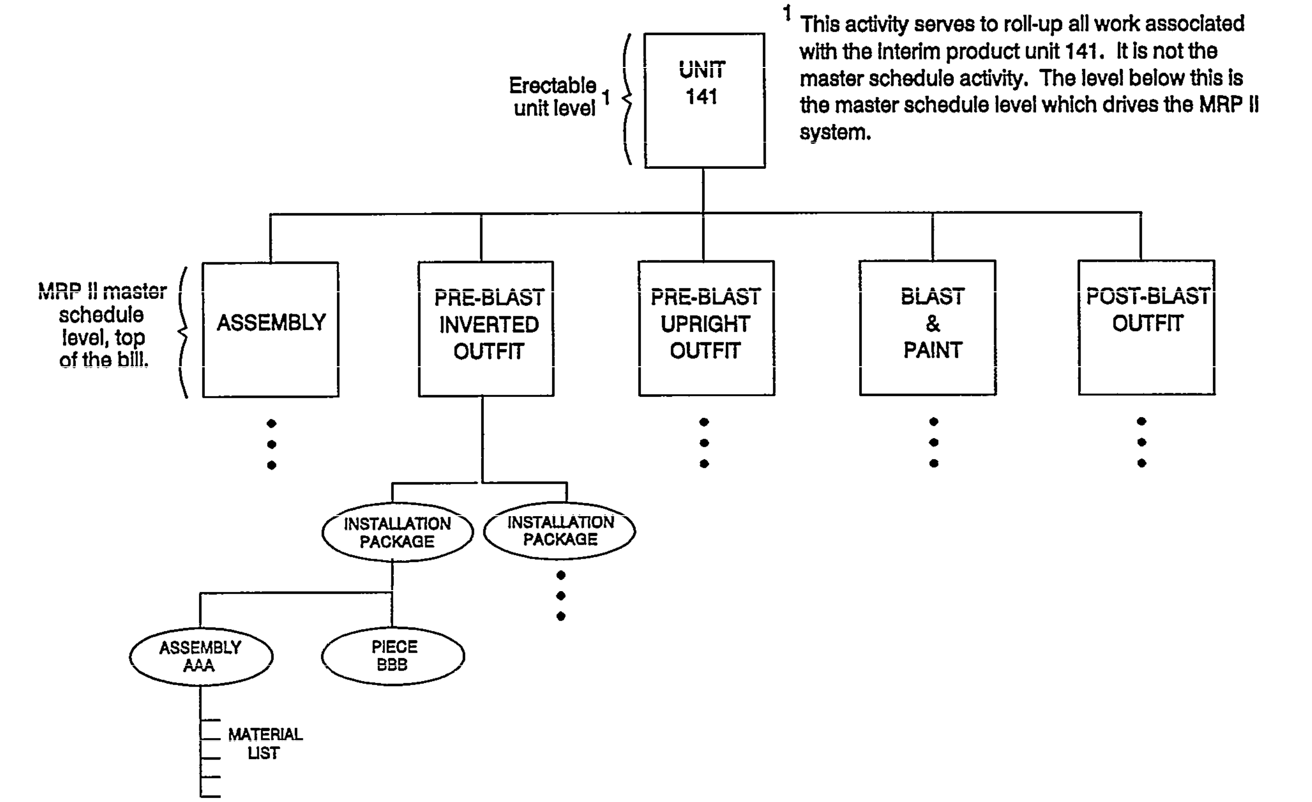


Figure 7: MRP II structuring for sample unit 141 based upon the master schedule activity network shown in Figure 5.

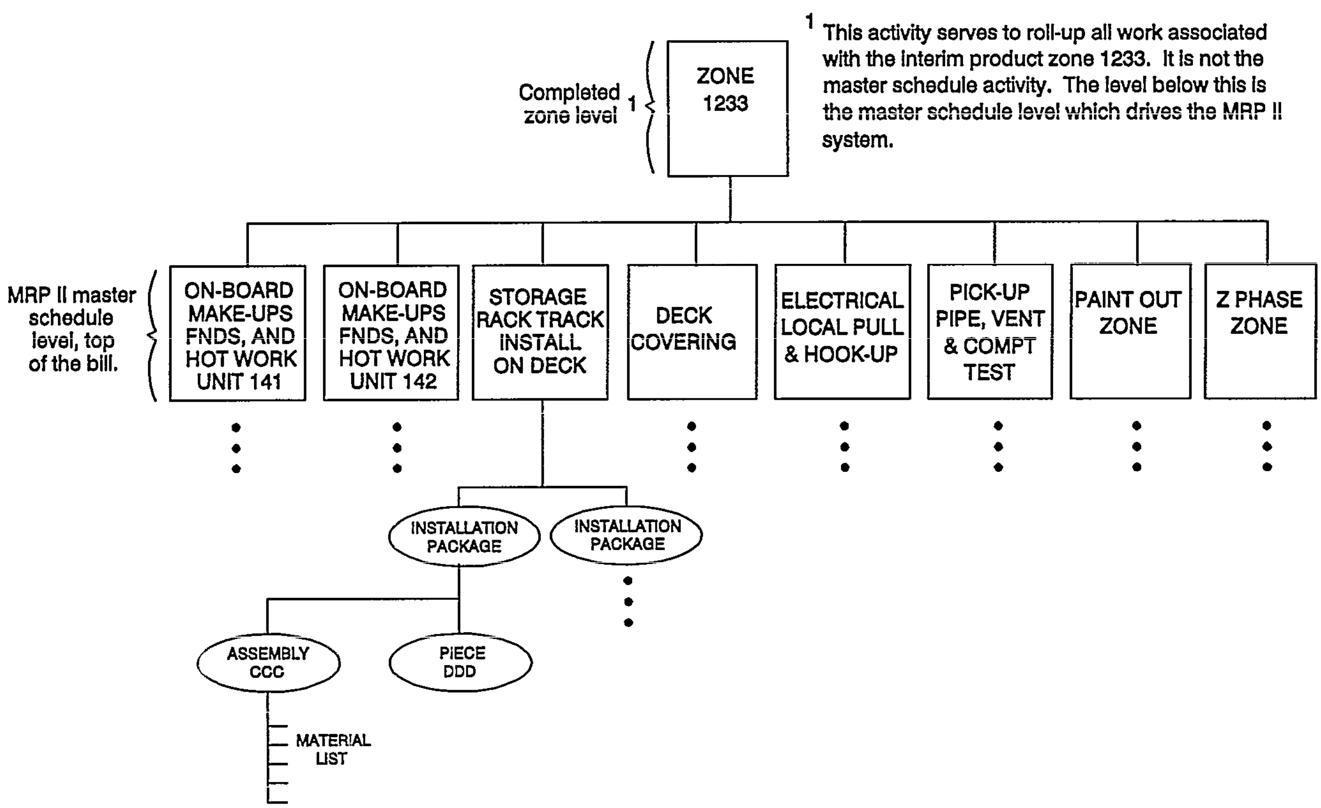


Figure 8: MRP II structuring for sample zone 1233 based upon the master schedule activity network shown in Figure 6.

SYSTEM USAGE

The master level scheduling network and the MRP II production control system serve different roles. These two systems must combine to serve material, production, and reporting needs. The combined systems must generate and update both high level and detailed schedules so as to provide production control. They must also serve to show material requirements and provide material control. The systems must facilitate internal and external reporting as well as allow for manpower and facility utilization planning. The functions performed by each system are shown in Table V.

To effectively perform these interrelated tasks, the systems must communicate with one another, and reflect a common strategy. The communication between these systems is illustrated in Figure 9. Dates generated by the master schedule activity network are fed into the top of the bill as "need dates" for the MRP II system. The MRP II system uses these dates in conjunction with the structured bill and process plan to create the production and material control schedule which drives shop floor execution to the plan. As work is accomplished, progress is entered into the MRP II system. Progress information is passed back to the master schedule activity network and the network is updated.

	MASTER SCHEDULE LEVEL ACTIVITIES	DETAILED PRODUCTION SCHEDULE	MANNING PLANS	MATERIAL REQUIREMENTS	PROGRESSING/ UPDATING	PRODUCTION CONTROL REPORTS
MASTER LEVEL SCHEDULING NETWORK	Created by network based upon build strategy and resource leveling.	———	Produced for key production areas as part of master schedule development and leveling.	Initiates procurement for selected long lead time items (eg. main engines, SSDG's.)	Progressed regularly so that realistic master schedules may be maintained.	Master schedules with regular updates.
MRP II	Reflects as top of bill.	Created in MRP II as an explosion of the structured bill.	———	Serves as material procurment/ control system.	Updated based upon changes to the master production schedule.	Dispatch sheets, work orders with detailed work instructions, and shop floor control paper.

Table V: Matrix showing tasks performed by the network and MRP II systems.

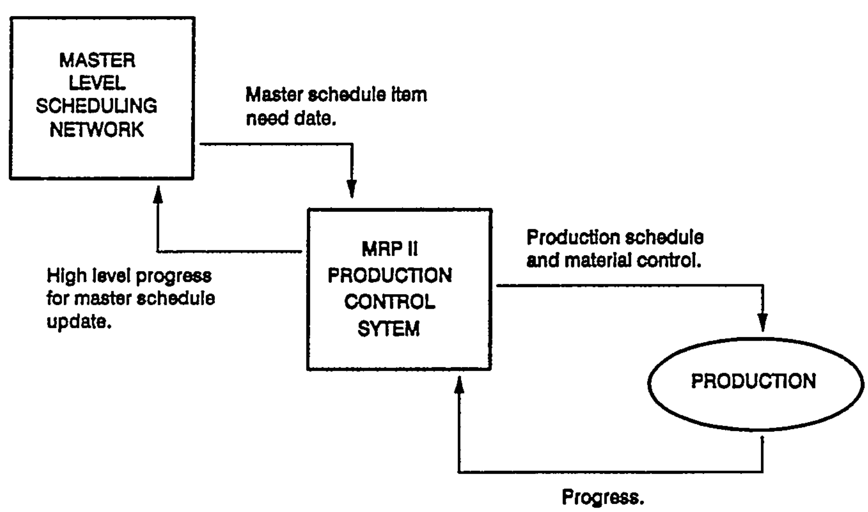


Figure 9: Communication between the network system, MRP II system, and production.

CONCLUSION

This presentation has explored two approaches to schedule development: the network schedule and the MRP II schedule. In the shipbuilding industry both approaches have a place. The network provides top level aggregate production planning, even if the supporting detail is not yet designed. This allows for planning and scheduling of activities outside of production. Indirect functions such as engineering, QA, and procurement of long lead time material can be controlled by network scheduling. The network is used to report status at a high level, assess the impact of change, and reschedule as deviation occurs. The network is the master production schedule used by MRP II. To the extent the product structure is defined, MRP II provides automatic schedule generation based upon the master production schedule. MRP II is the tool for material and production control. The network schedule and MRP II are both powerful tools. By using these tools together, a shipyard will be better able to plan and execute the ship construction process.

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Shell Development Computer Aided Lofting - Is There a Problem or Not?

Thomas Lamb (F)-Textron Marine Systems, a Division of Textron,Inc.

ABSTRACT

Some shipyards are not satisfied with the computer aided shell development systems that they use. This is because of fit up problems and the need for excess material to allow corrections to be made at erection. Most shipbuilders desire a "cut to neat size" approach.

Most CAL developers recommend that excess material be used. They claim that this is to take care of limitations in the plater's skill and the forming machinery, not in the CAL system.

The paper reports on a study that was undertaken to determine the correct perspective for the shell plate development problem and if the shipbuilder's goal of cutting all shell plates neat is reasonable.

NOMENCLATURE

BSRA	British Ship Research Association
CAL	Computer Aided Lofting
NASSCO	National Steel & Shipbuilding Company
N/C	Numerically Controlled
NSRP	National Shipbuilding Research Program
MarAd	Maritime Administration

INTRODUCTION

Computer aided shell plate development methods have been in use for approximately 30 years. At first the computer approaches simply duplicated the traditional manual ship lofting approaches. In fact, early versions of computer aided lofting systems emphasized this as an advantage, in the hope that the traditional lofstmen would be more willing to accept the "new" tool if they knew it emulated how they manually performed the same task.

The demand for improved accuracy, plus the evolving capabilities of computers and software, resulted in improvements to all the areas of computer aided lofting, including shell plate development.

Unfortunately, even with these improvements, most shipbuilders are still dissatisfied with the accuracy of the current computer shell plate development. The shipbuilders' goal is to cut every shell plate neat (with no excess material around the developed shape to allow for the inaccuracies at fit up). More specifically, they want to be able to erect a block to another block with the erection joints matching perfectly, thus minimizing rework at the erection stage. Most shipbuilders report that they cannot do this for shell plates with any shape other than simple curvature in the transverse direction, which can be simply rolled.

To help put the shell plate development problems in their correct perspective and to attempt to determine if the goal of cutting all shell plates neat is reasonable, a study was tided by the SP-4 Panel with the following objectives:

- To obtain the participation of existing shipbuilding and aerospace computer aided lofting system developers/users to discuss:
  - Shell development problems
  - The methods they use to develop shell plate and handle the problems
  - Any stipulated limitations in application
- To select five (5) shell plates representative of the "difficult" type as test cases to be developed by the participating computer aided lofting system developers.

BACKGROUND

The development of the shell plates of a ship has been a necessary shipbuilding skill since the introduction of iron ships. Early shipwrights/platers did not develop shell plates. The Ioftsmen laid the lines of frames on a screive board. Templates were then made for each frame from the Rune lines on the screive board. The actual flmes were then shaped to

the templates. Once the frames were erected and secured by the deck beams and ribbands, the shell plates were "lifted off" theframes by wood tip templates (patterns). The template was used to transfer the flat shape to the plate which was marked and then cut. As the seams and butts were either lapped or strapped and riveted , accuracy was not as essential as it became for welded ships and is today for modem shipbuilding methods. Also, the shape of the shell plates was kept as simple as possible by following the "natural" straking for the hull shape.

As can be well imagined this approach was very labor intensive. The practice of lofting and shell plate development from the full scale frame body plan on the loft floor was a natural development in the progress of shipbuilding technology at that time.

The first attempt to improve on the full scale lofting approach was the fairing of ship's lines by using the method of differences. This was a manual calculation approach that improved on the time taken to fair lines, but it was still labor intensive and required more highly educated technicians to apply it. Once the fairing was complete it was still necessary to lay down the frame lines on the loft floor and the development of shell plates and frame templates were lifted in the traditional manner.

The first major break from the traditional loft and lofting was the 1:10 scale lofting developed in Germany by Sicomat in the late 1950's. Some developments based on this approach were the optical projection of the 1:10 drawing to full scale on the plate for marking, and the electronic optical following controller that could direct a burning machine.

The manual development of shell plating required skilled and experienced loftsmen. In an attempt to improve on the manual method and to reduce dependence on skilled loftsmen, the G.A.G. Plate Development Jig was developed in Germany in the early 1960's. It was a logical development in parallel with the 1:10 lofting and burning machines.

About the time that the optical tracing 1:10 system was being put into practice, a number of organizations and countries were developing computer aided lofting (CAL) systems, and computer or numerical controlled burning and marking machines.

While the British and the Scandinavians were the most successful in putting CAL into practice, in the early 1960's, the U.S. did experiment with numerically controlled (N/C) burning machines at the Todd shipyard in Seattle under a MarAd funded study. Unfortunately for the U.S. nothing came of it.

The British system was developed by the British Ship Research Association (BSRA) which was jointly funded by the major British shipbuilders with significant support from the British government. Their charter was to develop systems that would give the British shipyards a competitive advantage through technology, so there was no interest to expand the use of BSW systems in other countries. In fact the opposite was the case.

On the other hand both the Norwegian AUTOKON and the Swedish STEERBEAR systems were marketed aggressively around the world. AUTOKON was marketed in the U.S. by COM/CODE CorporatiorL which had obtained the Iicence for it in the U.S. and Canada. COM/CODE licenced AUTOKON to Newport News in 1972, and in 1973 gave a special licence to MMA4 which in turn, could licence up to ten individual U.S. shipbuilders. However, the anticipated number of shipyards did not purchase the AUTOKON licences, perhaps because the decline in U.S. commercial shipbuilding had already started.

General Dynamics had been a user of the AUTOKON system before COM/CODE obtained their licence and continued to use it.

Bethlehem Steel shipyard instaIled an N/C burning and marking machine in 1966 and tried to develop its own system but was unsuccessful. In 1974 it joined the MarAd sponsored AUT-OKON users' group.

Avondale shipyard developed its own system under the direction of Fil Cali, which eventually developed into the SPADES system currently used by Avondale, Ingalls, Ma.rinette Marine, NASSCO, and Lockheed (before it closed).

Since then the different CAL systems have become more user friendly, efficient integrated and capable of providing shipbuilding oriented user data. With the exception of FORAN, which developed as a design system and then added lofting, these systems were first developed as a computer aided manufacturing (CAM) tool. Over the years they have been extended back into design and planning to offer a "total shipbuilding system."

Lofting methods developed for steel shipbuilding were used by early aircraft manufacturers. Both Boeing and McDonnel Douglas later developed their own CAL systems. Both of these systems have since been used for ship lofting and shell plate development but the results have been no better than that offered by the shipbuilding CAL systems.

In the last decade, simpler and lower cost systems for ship lofting have been developed with the aid of the personal computer. While these do not offer all the capabilities of the established total shipbuilding systems, they do offer a lower cost alternative for a

shipbuilder to obtain a CAL and N/C generating capability.

Today some shipbuilders still believe that there are definite limitations to the use of computer aided shell development systems. Blocks in tie modern modular shipbuilding approach are designed with transverse butts, and horizontal joining seams. This results in the joining plate having significant twist and backset in certain parts of the forward and aft lower shoulders. Some blocks constructed recently in the U.S. have been out of alignment by 2 to 3 inches at the comers of the block.

Some U.S. shipbuilders claim that the Japanese shipbuilders cut all plates neat and rdl blocks without stock and they fit! However, at the 1992 NSRP Symposium (1) it was reported that a major Japanese shipbuilding group were currently far from acheiving this goal. Sixteen to 30% of their formed shell plates required back stripping or cutting and they always left stock on bow and stem blocks. This is not too different from U.S. shipyard practice. Another Japanese shipbuilder is reported to leave only 1/4 inch when stock is required and if it fits well when erected to the adjacent block it is simply left on. Otherwise it is used for fit-up adjustment.

Most CAL system developers recommend that stock material be left on one seam and one butt for each block that has significant curvature. Many say this is to take care of inaccuracies due to the platers' skill level and limitations of the forming machinery, rather than compensate for inaccuracies in the plate development. Today, most shipbuilders desire a "cut to neat size" approach. This is obviously to eliminate labor intensive fitting, cutting in and edge preparation on the building berth or plattens. However, it appears unattainable. Why is this? The SP-4 Limitations of Computerized Lofting study was performed to attempt to answer if it is.

SHELL PLATE DEVELOPMENT PROBLEMS

In performing this study it was determined that shell plate development problems are viewed differently by shipbuilders and the CAL developers. This is surprising when it is remembered that computer aided lofting shell development methods have been in use for over twenty years. It would seem reasonable to expect developers and users (shipbuilders) to have worked out the problems or at least agreed what they are. However, as will be seen from the following discussion this does not appear to be the case.

Before discussing the problems, it is necessary to define some of the terms that will be used.

CURVATURE is smooth deviation from a straight line. As applied to a surface it is smooth deviation from a flat plane.

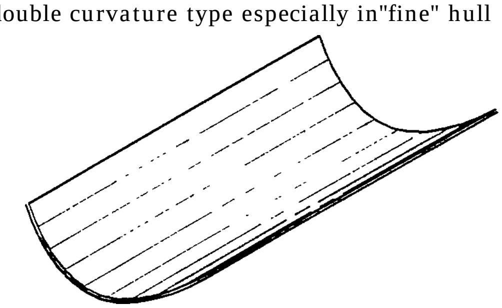
SINGLE CURVATURE is deviation in only one direction.

DOUBLE CURVATURE is deviation in two directions approximately normal to each other.

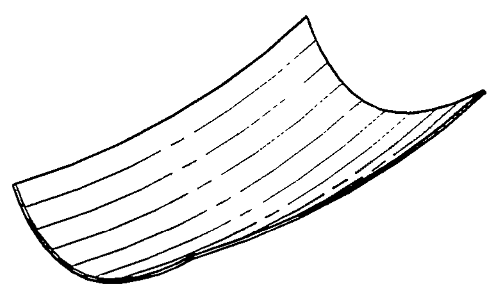
REVERSE DOUBLE CURVATURE occurs when curvature in the two directions is in opposite directions.

STOCK is excess material added to tie developed flat plate shape. It is usually a fixed allowance such as one inch offset from the developed shape of the seam(s) and butt(s).

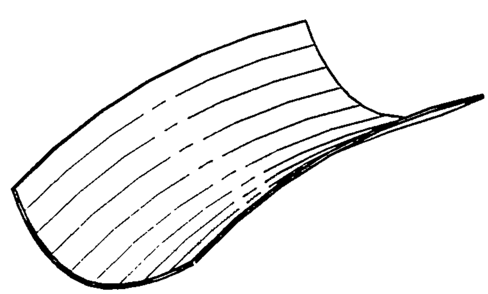
Figure 1 gives examples of plates with the above types of curvature. Shell plates in the parallel mid body at the bilge would be single curvature plates. Most other curved shell plates would be double curvature. Shell plates at the stem and stem can be reverse double curvature type especially in"fine" hull forms.



SINGLE CURVATURE



DOUBLE CURVATURE



REVERSE DOUBLE CURVATURE

Figure 1 Curvature Definitions

Modular construction divides a ship's hull into structural blocks. Figure 2 shows the aft portion of the block definition drawing for a typical single screw ship. Figure 3 shows the block above the propeller aperture upside down as it would probably be built. It contains shell plates with significant reverse double curvature as shown. It also shows the four erection seams, two transverse erection butts and the transom erection butt. The upper seams and the transom butt are in the same plane, a water line. The block contains a total of 15 shell plates.

U.S. Shipbuilding Situation

Most shipbuilders in the U.S. are not satisfied with the current shell development situation. They want to be able to cut shell plates neat, That is, without excess material to be "cut in" during fitting the plates on the assembly plattens or structural blocks on the building berth. They view their inability to do this as a limitation of current computer aided lofting systems shell development technology.

While a large number of a ship's shell plates will be flat in the "flat of side" and "flat of bottom,"and developable at the bilge radius in way of the parallel body, there are still many that have complex curvature. It should be obvious to most people involved in the design of ships that normal ship hull shapes do not have developable dates in the area of curved plates.

The following information, for a typical high speed container ship, gives an appreciation of the problem. It had 35,000 lofted parts. Forty-five percent, or about 16,000, are N/C cut parts. The number of shell plates on such a ship was about 800. The shipyard did <u>not</u> their CAL shell development program for about 80 shell plates located in the bow and stem. They used their experience to locate, strake and size these plates and manually develop them. Of these 80, half required forming over a built up "form, set or bed." This same shipyard reported particular problems with shell plates that contained both flat and compound curvature, such as plates crossing the flat of bottom or side tangency lines.

Table I contains similar data for a tanker taken from the Avondale/IHI Shipbuilding Technology Transfer data (2). From this it can be seen that only a small percentage (15. 1%) could be formed by just rolling. The majority of the plates required rolling and then tier forming by line heating. This is probably due to the decision not to use packed rolls for plates with back set, but rather to simply roll them first and use line heating to obtain longitudinal curvature. It should also be noted that a smaller number of actual plates were curved, 296 versus 800. This is because the first vessel had more shape throughout its length or less parallel body than the second ship.

Accuracy control has contributed to the better fit up of internal structure in subassemblies and structural blocks. However, because of the uniqueness of individual curved shell plates, the forming techniques and shape control used, it is difficult to apply the accuracy control process to shell plates. One possible application used by a Japanese shipbuilder for additional marking on shell plates is shown in Figure 4 (3). This method consists of providing a contiuous marking inside the seams and butts at a constant distance for every shell plate. After a shell plate is joined to another, and after the internal structure is completely welded to the shell plates, measurements can be taken from one line to its adjacent plate line, and the distance recorded. This would be applied to all the usual accuracy control analysis tools, and the results used to control the shell shaping/fitting process and to show when improvements were necessary. It would also provide the necessary raw data from which to develop weld shrinkage data.

1. Amount of curved shell plates (one ship)

Aft Construction Part	35 Plates*
Engine Room Part	84 Plates
Cargo Hold Part	112 Plates
Fwd. Construction Part	67 Plates*
TOTAL	298 Plates

NOTE * ESTIMATED FROM DRAWINGS

2. Classification of curved plates bending works

Bending Process	Plate Quantity	Percentage
a) No roll	26	8.7
b) Roller (or press) only	45	15.1
c) Roller and Line Heating	196	65.8
d) Line Heating Only	20	6.7
e) Roller and Forming jig	11	3.7
TOTAL	298	100.0

Rolls=b +c+ e=45 + 196+ 11 =252 plates/1 ship
Line Heating = c + d = 196+20=216 plates/1 ship

TABLE I - CURVED SHELL PLATES ON TANKER

Shipbuilders report that they have problems with individual shell plates fitting pin jigs or egg-crated support structure. Some report that the plate shape is acceptable but that the plate marking is out of alignment with internal structure. This has led them not to mark such plates by N/C, but using the IHI "Key Line" method to lay out the marking <u>after</u> the plates are formed, set on jigs and joined together. The IHI Key Line method was described in detail in the Avondale/IHl Technology Transfer reports (2). Some

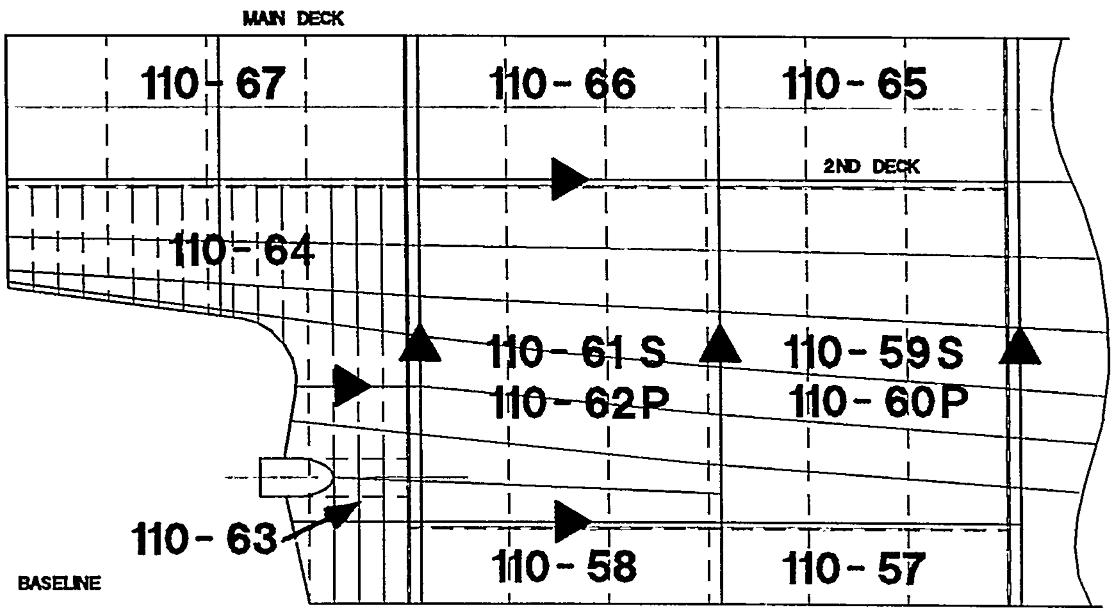


Figure 2 Block Definition Drawing

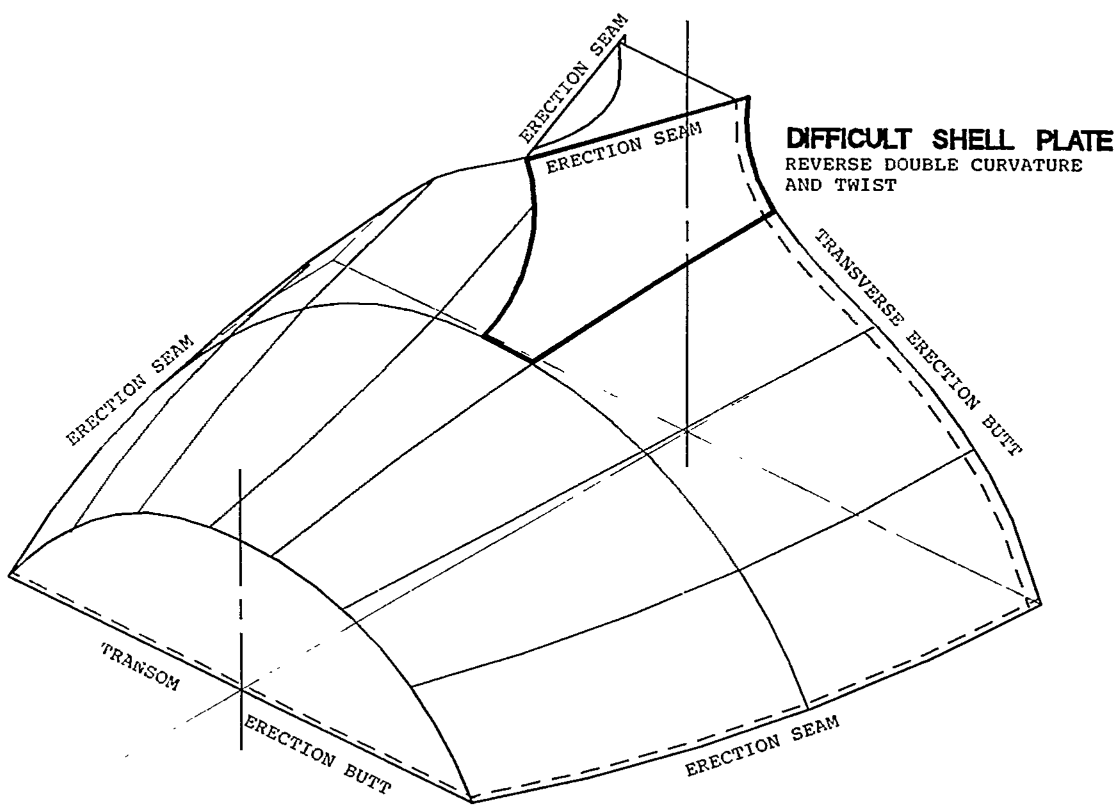


Figure 3 Isometric View of Block 110-64

shipyards use the Key Line method to - the N/C marking after the plates have been joined to form a panel.

Other shipbuilders have problems with the "squareness" of structural block shell plates. They report corners that are up to 3 inches out of true location on a typical block with curved shell plate.

Some shipbuilders report that a major cause of these problems is inadequate definition of the ship's lines, especially in areas of extreme compound curvature. This suggests that better definition through closer spacing of control lines (frames, waterlines and buttocks) is necessary, and better checking for fairness in these regions, and should be a normal part of the process of lines fairing. It is too late to discover bumps, hollows or knuckles in the hull surface during shell plate development. Because of this underdefined lines problem some shipbuilders use Ml scale mock ups to ensure smooth surfaces. Typical areas where this is done are:

- Segmented or "orange peel" plates such as spherical bulbous bow plates, and
- Plates with extreme twist.

The inability to consistently process shell plate with acceptable accuracy forces shipbuilders to "play it safe" and we "stock" on at least one butt and one seam-for the shell on each curved structural block. Then they must cut the stock material off, either as the blocks are aligned, or before erection, through the use of one of the current accurate measurement and alignment methods. Either method requires considerable skill and significant effort (man hours) and time (longer build duration) to accomplish the fit up, removal of the stock and preparing the edge for welding.

Problematic areas of a ship's hull, as identified by shipbuilders, are

- Clipper bows - soft nose stem,
- Cruiser sterns,
- Single screw apertures - stem frames,
- Forebody and aft body shoulders,
- Blocks in the fore and aft bodies with vertical butts and horizontal seams,
- Bulbous bows,
- Sonar domes, and
- Heavy flare in "fine" hulls

Some shipbuilders/designers avoid some of these problems by utilizing large castings, especially for stems and stem frames.

Computer Aided Lofting Developers' Experience

AU the participating CAL developers are aware of shell plate problems, but they do not see them as a limitation of the methods they use. They all point out that shell development of double curvature shell plates is an approximation. There is no exact "unwrapped" flat shape for such curved plates. However, they believe that the approximation gives developed flat shapes for plates that are well within current shipbuilding tolerances. A number of CAL developers stress that all shell plate development requires system-skilled and lofting-experienced users with knowledge of their shipyard's forming and fabrication capabilities and limitations.

Albacore Research recognizes that some extreme double curvature shell plates cannot be adequately expanded into a flat shape. They decide which plates cannot be developed by reviewing the fore and aft deflection of the transverse mesh lines, as shown in the shell expansion view produced by their system (Figure 5). The areas on the hull that cannot be developed show as clear areas, without the mesh.

BMT also recognize that specific areas of certain ship hulls require special attention from experienced Ioftsmen. These loftsmen should not only be experienced in the application of the CAL system but also with their shipyard's shell forming constraints. The BMT system also has an application wherein the direction and magnitude of the curvature are displayed by tufts of principal curvature for the hull surface patches.

Cali points out that "development of a compound curved surface into a flat pattern is a mathematical impossibility." Based on this, the problems are essentially lack of agreement on how much of an approximation is acceptable and lack of allowance by the shipbuilders to account for the inexactness of the approximation for specific shell plates. The accuracy of the approximation is significantly influenced by the selection of the seams and butts. The effect of straking to suit modular construction can create problems by twisting the shell plates. These problems are addressed by considering the correct "priorities" in defining the shell seams and butts. These priorities in correct order should be:

- Hull Form Complexity,
- Straking - Selection of butts at curvature inflexion points,
  Selection of block seams to suit hull shape, and
- Material Utilization.

Coastdesign addresses problems of using small craft developable surfaces when the designer's lines must be maintained. They point out that only the deck edge and the chines should be defined, since the fkame sections will be derived from the developable surfaces in the AutoPlex system. Also, the AutoPlex system

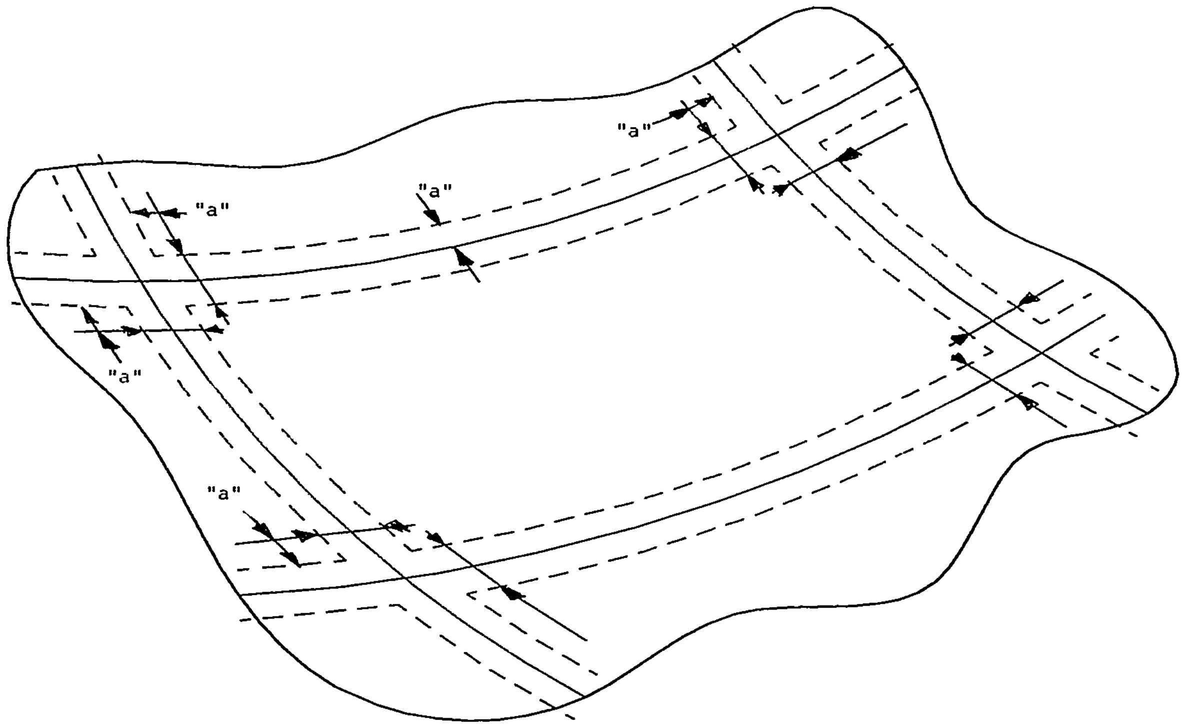


Figure 4 Use of Standard Plate Marking for Accuracy Control

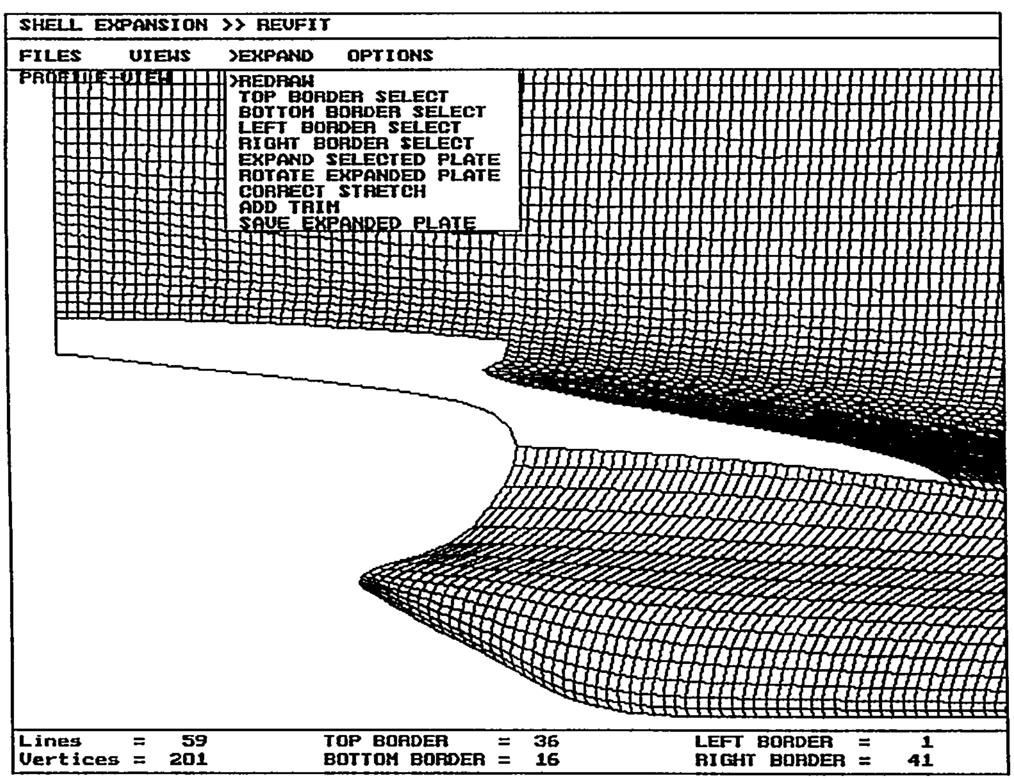


Figure 5 Stern of Vessel with Extreme Fore & Aft Deflections in Transverse Lines

ignores plating thickness. This presents no problem when plating thickness is small. When using thick shell plates, it is possible to overcome this problem in AutoPlex by contracting or expanding the hull lines to account for the plating thickness. Forming of compound curvature plates is basically accomplished by applying strain to the flat plate to deform it into the designed shape. Theoretically, the development of such a plate could be made exact by using a finite element method. However, there is no practical method of applying the strain to the plate exactly as required. Also the resulting deformation would increase and decrease the plate thickness as the plate material was stretched or compressed. Strain maps are produced by the system as the shell development uses a finite element approach. They can be used in the forming process by showing where most of the strain and thus the application of the deforming force should be applied.

Kockums Computer System report that most known shell plate problems can be resolved by correctly orientating individual plates to the expansion curves by using smaller plates where curvature is large. The AUTOKON system's interactive capability makes it relatively easy to try different approaches for the development of difficult shell plates such as smaller plates, transverse expansion curves as an alternative to longitudinal expansion curves, and closer spacing of the expansion curves.

Senermar points out that one of the main problems with shell plate development and forming is the verification of the plate shaping. Of interest is their use of a longitudinal template with transverse roll sets as a means for better control. Senermar also compensates for weld shrinkage, and their system can take care of it in two ways. First,they compensate for weld shrinkage in both the transverse and longitudinal directions by either the same or different shrinkage factors, as selected by the user, and all coordinates of the developed shell plate are automatically adjusted. Second, instead of shrinkage factors, a constant allowance can be added to any of the plate edges.

Foreign Shiubuilfing Situation

Although four foreign shipbuilders were invited to participate in this study, they all declined. As an alternative, papers presented by foreign shipbuilders on the subject were reviewed to obtain some idea of their views (4, 5 & 6). From this review, and personal discussions between them and the author, it can be stated that they do not see the shell development problem as much of a problem as some of the U.S. shipyards see it.

Their message is that successful shell plate forming and erection is as much or more dependent on the material handling and forming equipment, and the skills and training of the forming and erection workers, as it is on the computer aided lofting method accuracy.

Aircraft Industrv Plate DeveIopment Problems

The aircraft industry has some problems that are similar to shipbuilding and others that are unique. As already reported, early aircraft lofting used shipbuilding lofting techniques and loftsmen. Most existing aircraft manufacturers now have their own computer aided lofting system which have been designed to handle their unique needs.

The simple shaped plates in the fuselage, wings and tail present no problems. It is the leading edges of the wings and tail, forward and aft ends of the fuselage and engine nacelle leading edge that require special treatment.. The problems are dealt with by using one of the following approaches:

. Sheet stretching or hammer forming over dies,

. Sheet shot peening, or

. Composite molds.

Where plate development is performed it is done by multiple triangulation and stock is provided for fit up.

DESCRIPTION OF CAL SHELL PLATE DEVELOPMENT METHODS

The six participating CAL developers can be grouped into two PC based and four main frame based systems. However, all the main frame based systems are currently offering stand alone and networked work station versions of their systems.

All systems except Senermar's FORAN use triangulation of many small panels formed by four 3-D space points to obtain the flat developed shape of the plate. However, each uses a slightly different application. Senermar uses a unique approach of building up the Surface definition for each plate from a number of analytical mathematical surfaces, and then developing each one of the set of surfaces and nesting them together to obtain the flat developed shape of the plate. The SPADES system starts its development at one end of the plate, whereas all the others start in the middle.

All systems except ShipCAM3 and AutoPlex/AutoPlate automatically take care of plate thickness and its location relative to the molded line.

All programs provide an N/C code output and a hard copy sketch of the developed plate and its marking. However, ShipCAM3 requires the use of an independent CAD system to accomplish this. They all provide manufacturing aid information. ShipCAM3, AutoSHIP and AUTOKON all offer different versions of plate strain information which can be used by the plate developer to help decide if developed plate is acceptable, and by the forming operator to show where the deforming force should be applied and to what extent.

Table II presents a summary of the participating CAL developers shell development systems.

A detailed description of the shell plate development methods used by the participating CAL developers will be included in the published study report.

CAL SHELL PLATE DEVELOPMENT LIMITATIONS

All of the participating CAL developers were requested to report limitations of their shell development system. They were asked to report on shell plate limitations such as:

- . Maximum or minimum length,
- . Maximum or minimum width,
- . Plate thickness,
- . Maximum backset,
- . Minimum curvature in any direction,
- . Limit of twist,
- . Ratio of backset to length,
- . Ratio of curvature to width, and
- . Ratio of minimum curvature to plate thickness.

As it turned out the items suggested in the above list were not limitations for most of the CAL systems.

While Albacore's system has only been in use for a few years, they have not yet encountered any limitations. However, their system does not currently automatically adjust for plate thickness.

BMT also has no real system limitations. Actual shipyard installation capabilities are dictated by the available material size and handling/processing capabilities of the shipyards rather than their system. Based on this experience BMT suggests the following “practical limitations”:

Maximum length	20m	(66 feet)
Maximum width	5m	(16 feet)
Maximum back set	4cm	(1.5 inches) for rolled plates

BMT also points out that special treatment must be given to soft nose stem and transom plates due to their basic shell development approach rather than degree of "difficulty" of the plate shape.

Coastdesign advises that the AutoPlex system is only intended for developable surfaces, and thus cannot handle reverse double curvature plates such as a flared bow even in a hard chine hull form. Their system also requires that chines must be plate boundaries. The AutoPlate system is unable to give a rolling line because of the development approach and it cannot develop a plate with more than 4 sides. Also, it cannot automatically add stock and plate thickness is not taken into account.

The AUTOKON system limitations are only in the area of number of expansion curves and the number of subdivisions for each expansion curve. However, these are well beyond the needs of any shell plate.

FORAN ha two limitations. The first is for spherical surfaces of small radius, which can, however, be handled by dividing the plate into two smaller plates. The second concerns the angle between the transverse tangents at the upper and lower seams. If this is greater than 90 degrees the plate must be divided into two plates by adding a seam. It is possible to join the two developed parts of the plate by nesting, and avoid cutting the added seam.

Table III presents a summary of the limitations of the participating CAL developers shell development systems as reported by them.

SELECTION OF FIVE TEST CASES

General

Five potentially difficult shell plates were selected for actual development by the participating CAL developers. Rather than generating five new hypothetical plates, these were selected from samples offered by the participating CAL developers. There was no intent to evaluate any of the development results. The resulting data is simply presented for review and use by interested readers.

Description of Rewired Test Cases

The participating CAL developers' reports confirmed the early definition of ‘difficult’ shell plate regions on a ship's hull. The five test case shell plates are,.

Case 1 (Figure 6) is a plate in the region where the normal hull shape in the bow transitions into the top of a bulbous bow. It involves reverse double curvature and twist.

COMPANY'S NAME	ALBACORE RESEARCH	BMT ICoNS LIMITED	CALI & ASSOCIATES, INC.
SYSTEM'S NAME	ShipCAM3	BRITSHIPS	SPADES
AVAILABLE SINCE	1990	1966	1973
USER INTERFACE	INTERACTIVE GRAPHICS	INTERACTIVE GRAPHICS	INTERACTIVE GRAPHICS
HARDWARE REQUIREMENTS	PC	MAINFRAME, WORK STATION AND PC	MAINFRAME ANDWORK STATION
DATA INPUT	FROM OFFSETS VIA SYSTEM FAIRING PROGRAM. ALSO FROM OTHER SHIP CAD SYSTEMS.	FROM SYSTEM FAIRING AND HULL SURFACE DEFINITION PROGRAM.	FROM SYSTEM FAIRING PROGRAM
SURFACE MODELLING	MESH USING 4TH ORDER B-SPLINES GENERATES 3D VERTICES ON SURFACE. VERTICES JOINED BY STRAIGHT LINES.	SURFACE DEFINED BY BI-CUBIC B-SPLINE PATCHES. TYPICALLY 50 PATCHES FOR ONE SIDE OF A SHIP'S HULL. A NET OF SURFACE 3D POINTS FOR ALL DEFINED SURFACE CURVES IS USED FOR THE SHELL PLATE DEVELOPMENT. NET POINTS ARE JOINED BY SPLINES.	GRID OF 2-D CURVES (TRANSVERSE AND ARBITARY LONGITUDINAL) PLUS 3-D BOUNDARY CONDITION CURVES
SHELL DEVELOPMENT APPROACH	COSINE LAW SINGLE TRIANGULATION OF STRAIGHT LINES BETWEEN VERTICES. STARTS IN MIDDLE OF PLATE AND DEVELOPS MESH COLUMN (TOWARD SEAMS),THEN SUCCESSIVE MESH COLUMNS TOWARDS BOTH BUTTS. MAINTAINS GIRTH LENGTHS OF MESH CONSTANT AND TAKES ACCOUNT OF ALL DEVELOPMENT DEFORMATION IN LONGITUDINAL DIRECTION.	SINGLE TRIANGULATION FOR EACH SET OF FOUR NET POINTS. STARTS IN THE MIDDLE OF THE PLATE, DEVELOPS TOWARDS THE SEAMS AND THEN ALONG A CENTRAL BAND TOWARD BOTH BUTTS. REMAINING FOUR PORTIONS OF PLATE ARE DEVELOPED IN A WAY THAT TENDS TO MAINTAIN THE OVERALL SEAM AND BUTT LENGTHS TO PRESERVE MATING WITH ADJACENT PLATES	USES BOTH GIRTH LENGTH FOR SIMPLE PLATES AND SINGLE TRIANGULATION FOR COMPOUND CURVATURE PLATES. WORKS FROM PLATE END CLOSEST TO AMIDSHIPS. a GRID OF UP TO 9 BY 50 POINTS IS USED FOR COMPUTING SURFACE DISTANCES BETWEEN POINTS. THE COMPUTED DISTANCES ARE THE USED TO TRIANGULATE THE POINTS INTO THE EXPANDED PLANE. TRIANGULATED POINTS ARE EVENTUALLY CURVE FITTED TO CREATE THE FINAL OUTPUT OF THE PLATE OUTLINE AND ALL INTERNAL LAYOUT.
PLATE MARKING	ONLY MARKS WATERLINES, FRAMES AND BUTTOCKS ON PLATE	ANY DEFINED CURVE/LINE ON SURFACE. ROLL LINE AND SIGHT LINE (OPTIONAL)	ANY DEFINED CURVE/LINE ON SURFACE AND ROLL LINE
UNIQUE ATTRIBUTES	STRAIN MAP. LONGITUDINAL DEFORMATION TABLE.	ABILITY TO ASSESS FAIRNESS OF SURFACE CURVES AND LOCAL SURFACE CURVATURE. PLATE CAN HAVE UP TO 8 SIDES TRIANGULATION ASPECT RATIO VARIATION WARNING. PROVISION OF CHECKING DIMENSIONS. ABILITY TO HANDLE ZERO GIRTH BUTTS. CAN HANDLE 8 SIDED PLATES. INPUT AND OUTPUT UNITS CAN BE DIFFERENT. CAN ADJUST FOR WELD SHRINKAGE	USE OF OPTIONAL REVERSE END DEVELOPMENT AS A CHECK ON NORMAL DEVELOPMENT. EXTENT OF DIFFERENCE CAN BE USED TO DECIDE NEED FOR STOCK. USES OPPOSITE DIAGONAL AS A CHECK ON GRID DISTORTION.

TABLE II - PARTICIPATING CAL DEVELOPER SYSTEM DESCRIPTION SUMMARY

COMPANY'S NAME	COASTDESIGN, INC.	KOCKUMS COMPUTER SYS. AB	SENERMAR
SYSTEM'S NAME	AutoSHIP	AUTOKON	FORAN
AVAILABLE SINCE	1972	1968	1972
USER INTERFACE	INTERACTIVE GRAPHICS	INTERACTIVE GRAPHICS	INTERACTIVE GRAPHICS
HARDWARE REQUIREMENTS	PC	MAINFRAME WORK STATION	MAINFRAME WORK STATION
DATA INPUT	FROM HULL DESIGN AND FAIRING SYSTEM PROGRAM	FROM SYSTEM DESIGN AND FAIRING PROGRAM	FROM SYSTEM DESIGN AND FAIRING PROGRAM
SURFACE MODELLING	USES 1ST, 2ND AND 3RD ORDER B-SPLINES IN TRANSVERSE DIRECTION AND CUBIC POLYNOMIAL SPLINES IN LONGITUDINAL DIRECTION.	3D MODEL OF SHIP'S HULL CONSISTING OF SCULPTURED AND PLANAR SURFACES. SCULPTURED SURFACE STORED AS MESH OF LINES	3D MODEL OF SHIP HULL CONSISTING OF PARAMETRIC SURFACES
SHELL DEVELOPMENT APPROACH	AUTOPLEX DEVELOPABLE SURFACE PROGRAM DETERMINES RULE LINES BETWEEN LONGITUDINAL KNUCKLE CURVES. AUTOPLATE FOR COMPOUND CURVATURE PLATES USES A PATENTED FINITE ELEMENT METHOD TO EXPAND SURFACE PATCHES WHICH ARE REPRESENTED BY 3D POINTS OR NODES. THE GEODESIC CURVE LENGTH (GEODESIC CURVE IN 3D IS STRAIGHT LINE IN 2D) BETWEEN NODES AND USES IT IN A SILIMAR WAY TO SINGLE TRIANGULATION.	USES GRID OF EXPANSION CURVES AND CROSSING CURVES. EXPANSION CURVES ARE SEGMENTED INTO 4 TO 20 PARTS GIVING 5 TO 21 3D POINTS ON EACH EXPANSION CURVE. PATCH OF PLATE BETWEEN EACH EXPANSION CURVE AND EACH CROSSING CURVE IS DEVELOPED BY TRIANGULATION USING TRUE GIRTH LENGTH ON THE EXPANSION CURVES AND CIRCULAR INTERPOLATION BETWEEN OTHER CURVES. OBTAINS 2D POINTS FOR DEVELOPED PLATE VIA COON'S PATCHES FOR 3D GRID	TRANSFERS HULL SURFACE FOR EACH PLATE INTO SETS OF DEVELOPABLE SURFACES (CYLINDERS AND CONES). USES NET OF 65 POINTS DETERMINED BY INTERSECTION OF 13 TRANSVERSE CURVES AND 5 LONGITUDINAL CURVES. FIRST CHECKS FOR CYLINDRICAL FIT OF SURFACE. IF NOT ACCEPTABLE FITS TWO CONIC SURFACES WITH COMMON GENERATRIX. CHECKS MEAN SQUARE ERROR AND DEVIATION BETWEEN REAL AND ADJUSTED SURFACES. MAY SELECT MORE THAN TWO CONIC SURFACES IF VALUE OF GAUSSIAN CURVATURE IS GREATER THAN A PREDETERMINED VALUE. THIS ALL OCCURS AUTOMATICALLY BASED ON MANY YEARS OF EXPERIENCE WITH THE SYSTEM.
PLATE MARKING		ANY DEFINED CURVE/LINE ON SURFACE AND ROLL LINE	ANY DEFINED CURVE/LINE ON SURFACE AND ROLL LINE
UNIQUE ATTRIBUTES	STRAIN MAP	USER OPTION TO SELECT DIRECTION AND NUMBER OF EXPANSION CURVES. CAN HANDLE PLATES CROSSING CENTER LINE. CAN HANDLE UP TO 99 SIDED PLATES. CAN ADJUST FOR WELD SHRINKAGE. CALCULATES STRETCH AND COMPRESSION IN FORMED PLATE.	CAN HANDLE BUTTS THAT ARE NOT PARALLEL TO FRAME LINES. CAN ADJUST FOR WELD SHRINKAGE.AUTOMATICALLY REORIENTS PLATES IN WAY OF FLAT OF SIDE AND BOTTOM TANGENCY LINES TO AVOID HIGHVALUES OF DERIVATIVES OF 3D POINT CONVERSION TO 2D POINTS.PRODUCTION AIDS SUCH AS FLAG TO SHOW IF PLATE CAN BE CUT WITH PARALLEL TORCHES. CHECKING DIMENSIONS AUTOMATICALLY GIVEN TO IMPROVE PLATE USAGE DURING INTERACTIVE PROCESS.

TABLE II (CONTINUED)

COMPANY'S NAME	ALBACORE RESEARCH	BMT ICONS LIMITED	CALI & ASSOCIATES, INC.	COASTDESIGN, INC.	KOCKUMS COMPUTER SYS. AD	SENERMAR
SYSTEM'S NAME	shipCAM3	BRITSHIPS	SPADES	AutoSHIP	AUTOKON	FORAN
SYSTEM LIMITATIONS						
MAXIMUM LENGTH		TYPICALLY (20M)66FT			(33M)1OOFEET	
MINIMUM LENGTH		TYPICALLY (1 M)3FT				
MAXIMUM WIDTH		TYPICALLY (3 M)16FT			(33M)IOOFEET	
MINIMUM WIDTH		TYPICALLY (1 M)3FT				
MAXIMUM BACKSET		(4CM)L5 INCHES				
OTHER	PLATE BOUNDARIES MUST BE EITHER MESH LINES OR PARALLEL TO 3 PRINCIPAL PLANES DOES NOT HANDLE PLATE THICKNESS AUTOMATICALLY CAN ONLY MARK WATERLINES, FRAMES AND BUTTOCKS. DECKS WITH CAMBER/SHEER AND LONGITUDINALS CANNOT BE MARKED NO ROLL LINE, ROLL SETS OR PIN JIG CAPABILITY MUST BE TRANSFERED TO A CAD SYSTEM FOR DETAILING ONLY ADDS STOCK TO BUTTS. NO CAPABILITY TO ADD STOCK TO SEAMS	SYSTEM USUALLY BASED ON A FRAMES DEFINITION (BUTTOCK VIEW) OF SHELL PLATE. HOWEVER PLATES CAN OPTIONALLY BE DEFINED ON WATERLINES TO HANDLE SOFT NOSE STEM PLATES. TRANSOM PLATES REQUIRE INTER-MEDIATE MANIPULATION	MAXIMUM OF 8 SEGMENTS PER TRANSVERSE CURVE SHELL PLATES LIMITED TO TWO SEAMS AND TWO BUTTS. PLATES WITH MORE BOUNDARIES OR WITH BUTTS THAT ARE NOT PARALLEL TO FRAMES MUST BE DEVELOPED IN PART GENERATION PROGRAM	DOES NOT HANDLE PLATE THICKNESS AUTOMATICALLY DOES NOT ADD STOCK DOES NOT HANDLE PLATES WITH MORE THAN FOUR BOUNDARIES MUST BE TRANSFERED TO CAD SYSTEM FOR DETAILING NO ROLL LINE, ROLL SETS OR PIN JIG CAPABILITY	MAXIMUM NUMBER OF EXPANSION CURVES IS 100 MINIMUM OF 4 AND MAXIMUM OF 20 SEGMENTS PER EXPANSION CURVE	SMALL IUUXUS SPHERICAL SURFAC MUST BE DIVIDED SMALL PLATES EXTREME TRANSVERSAL CURVATURE SUCH THAT ANGLE BETW TRANSVERSE TANGENTS AT UPP AND LOWER SEAMS LESS THAN 90 DEGI MUST BE SPLIT INT TWO PLATES BY ADDING A SEAM PR4CTICAL LIMITATIONS OF SHIPYARD TOOLS A DEFINED IN STAND PRODUCTION METHODS. WARNING MESSAG CAN BE PROVIDED.

TABLE III - LIMITATIONS OF PARTICIPATING CAL DEVELOPERS SHELL DEVELOPMENT SYSTEM SUMMARY

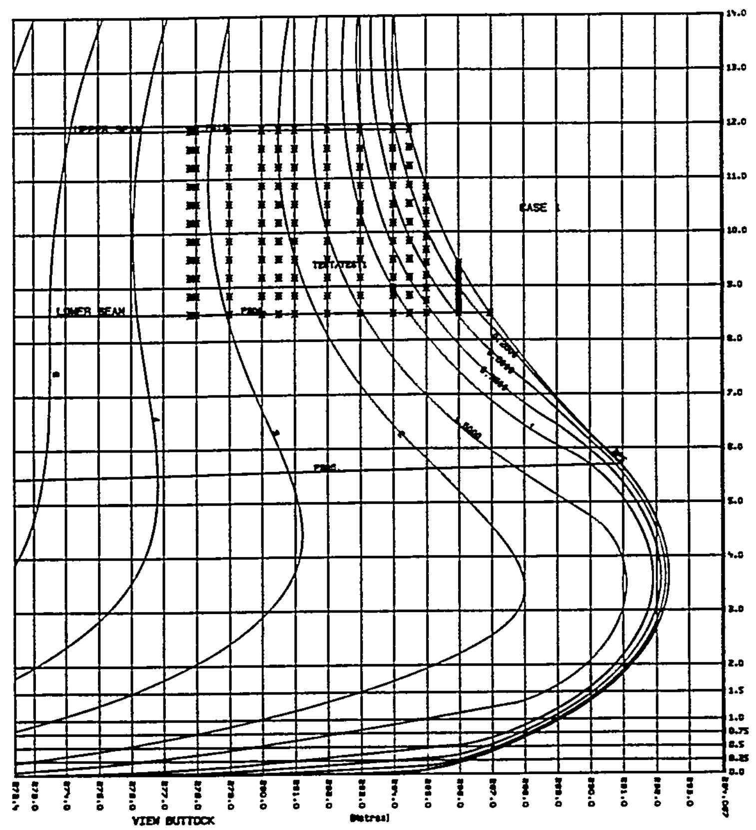


Figure 6 Case 1 - Plate above a Bulbous Bow

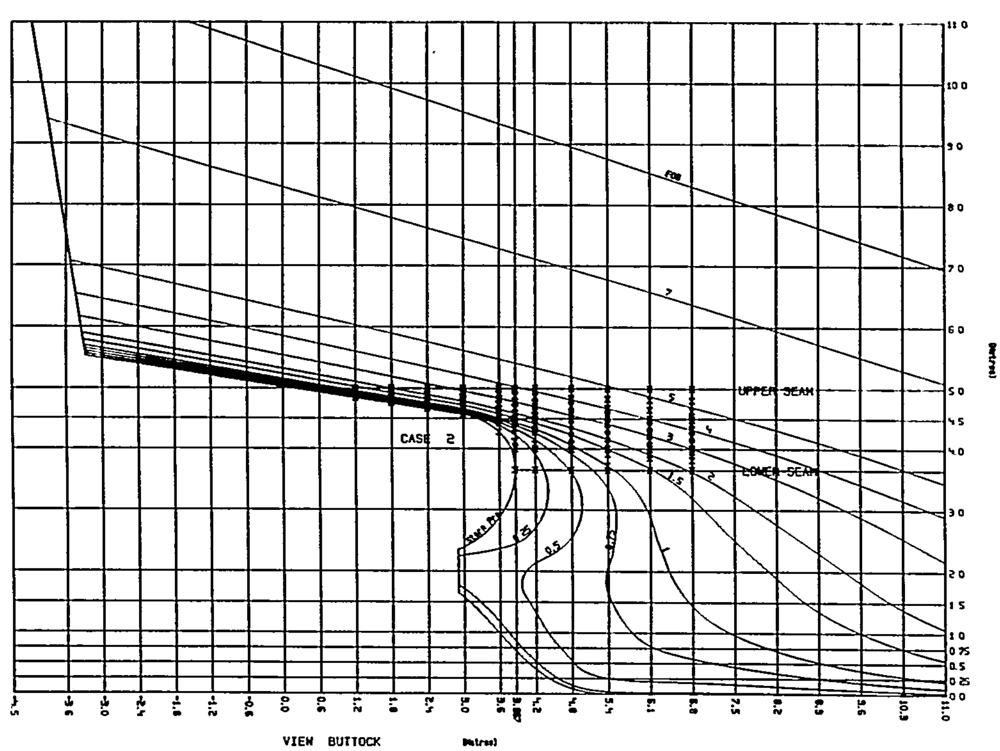


Figure 7 Case 2 - Plate in way of Stern Aperture

Case 2 (Figure 7) is a plate in way of the top of a single screw aperture. It involves more than 4 sides, both reverse and regular double curvature and twist.

Case 3 (Figure 8) is a plate in way of the hull shoulder close to the flat of bottom tangency curve. It only involves double curvature.

Case 4 (Figure 8) is a plate where the upper seam is the erection seam and is in the horizontal plane to suit block construction. It involves double curvature and twist.

Finally, Case 5 (Figure 9) is a plate which is adjacent to the underhung, faired bulbous bow, sonar dome found on many current warships. It also involves reverse double curvature and twist.

For each of the five test cases, the following data was be provided to and used by each participating CAL developer:

1. OIXsets for sections, waterlines and buttocks in way of each plate.
2. IGES format hi-cubic B-spline surface patches in way of each plate.
3. Definition of seams and marking curves.
4. Body, profile and plan views for each plate labeled for seams, butts and marking curves.

FIVE TEST CASE RESULTS

As the paper deadline neared, only three of the six participating CAL developers had completed the development of the five test cases.

As a quick comparison of the different developments the 1:10 scale plots of the developed plates were examined. For test cases 1, 3 and 4 there were no observable dfferences. Even the roll lines matched. However, for test cases 2 and 5 the difference was noticable, and for test case 5, which is the most complex plate of the five tested, there were considerable differences.. Figure 10 shows the test case 5 developed plate outlines superimposed on each other, and the difference in shape can be easily seen.

As a more precise comparison, the corner coordinates of the developed plates were tabulated and compared. They are shown in Table IV.

The differences are up to 50 millimeters in length and 25 millimeters in Widm for test cases 1, 3 and 4. The significant differences, in shape, for test case 5 described above, can be clearly seen by the significant differences in the comer coordinates. However, it should be mentioned that all three CAL developers recommended that this complex plate should be split into three plates. All six participating CAL developers have been asked to do this, but the redevelopments were not received in time to be included in the paper.

This lack of agreement by the three diferent CAL systems, cleary shows the need for stock (excess material) on such complex shell plates. Also, the amount of stock should be at least 100 millimeters to cuver the greatest differences.

STUDY CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Shell development problems are viewed differently by shipbuilders and CAL developers. As computer aided shell plate development methods have been in use for over 20 years, it would seem reasonable to expect developers and users (shipbuilders) to have worked together on the problems, or at least be in agreement as to what they are.

Foreign shipbuilders do not show the same concerns as some of the U.S. shipbuilders. Their message is that successful shell plate forming and erection is as much or more dependent on the material handling and forming equipment, and the skills and training of the forming and erection workers as it is on the computer aided lofting method accuracy.

While improvements have been made to all of the CAL developers' shell development systems over the years of use, they have been in the user interface and to take advantage of computer improvements. There has been no major new approach that significantly added to the accuracy of the developed plate flat shape.

The CAL systems are not "expert systems" nor do they inco~orate "artificial intelligence." This means that the use of the system and specifically shell development will be highly dependent on the user's skill level as a loftsman as well as experience with the system.

For most of the compound curvature shell plates on a ship's hull, the accuracy of the shell development systems is well within normal shipbuilding tolerances.

The shipbuilders' goal, to cut all shell plates neat probably will not be realized in the foreseeable fhture. This is due to two facts, namely

1. It is mathematically impossible to develop an exact flat pattern for any plate with compound curvature.
2. Shipbuilding plate forming tools and operator skills do not have the required consistent and repeatable accuracy.

The development of the same plate by different CAL systems is surprisingly inconsistent and gets progressively worse as the shell plates become more complex. However, even in this case the consistency

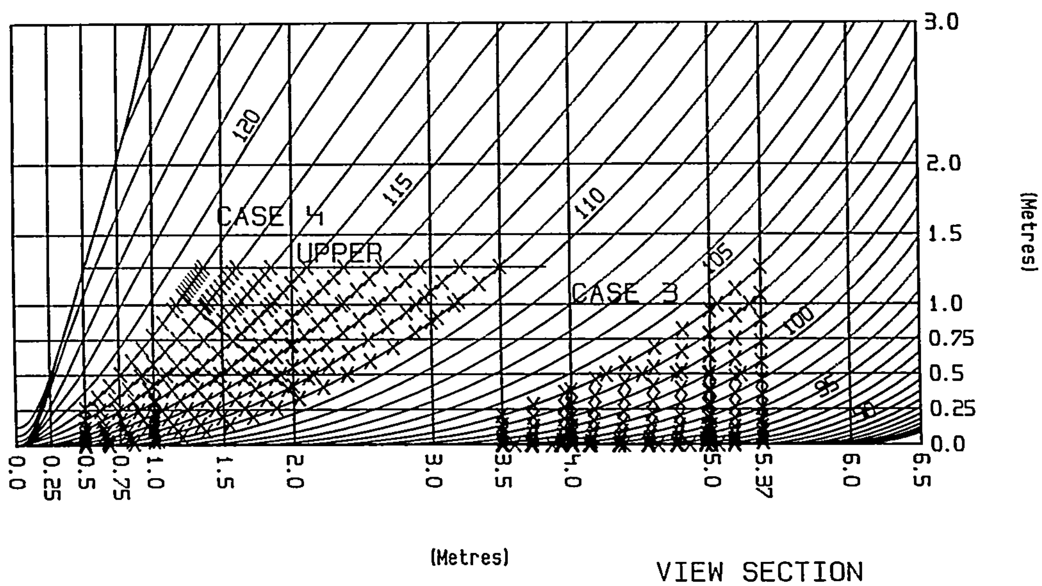


Figure 8 Cases 3 & 4 - Plates in way of Hull Shoulder and Bottom Flat Tangency

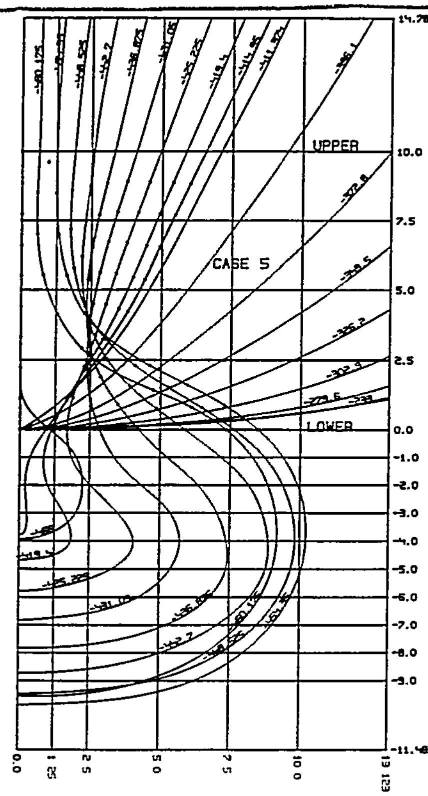


Figure 9 Case 5 - Plate in way of Sonar Dome

	BOTTOM LEFT	TOP LEFT	TOP RIGHT	BTM RIGHT	BTM CENTER
TEST CASE 1					
BMT	0/0	0.027/3.785	5.184/3.506	6.469/0	
FORAN	0/0	0.017/3.405	5.222/3.507	6.469/0	
KCS	0/0	0.007/3.389	5.202/3.587	6.488/0	
TEST CASE 2					
BMT	0/0	0.818/1.019	7.912/0.949	5.753/-2.198	2.159/-2.261
FORAN	0/0	0.797/1.016	7.890/0.946	5.741/-2.195	
KCS	0/0	0.825/1.013	7.532/1.100	5.643/-2.268	2.079/-2.268
TEST CASE 3					
BMT	0/0	0.041/1.874	8.555/2.057	8.408/-0.106	
FORAN	0/0	0.047/1.865	8.587/2.067	8.401/-0.111	
KCS	0/0	0.026/1.871	8.548/2.066	8.408/-0.099	
TEST CASE 4U					
BMT	0/0	-0.090/1.720	5.649/0.253	5.703/0	
FORAN	0/0	-0.085/1.743	5.718/0.245	5.710/0	
KCS	0/0	-0.079/1.741	5.713/0.257	5.693/0	
TEST CASE 4L					
BMT	0/0	0/1.593	5.699/1.091	5.611/0	
FORAN	0/0	0/1.590	5.708/1.072	5.611/0	
KCS	0/0	0/1.592	5.679/1.082	5.609/0	
TEST CASE 5					
BMT	0/0	1.330/2.528	16.470/2.528	16.509/-0.978	
FORAN	0/0	0.035/3.503	15.139/3.503	16.347/0.808	
KCS	0/0	0.567/3.492	14.358/3.488	16.134/1.090	

TABLE IV - COMPARISON OF DEVELOPED PLATE CORNER COORDINATES

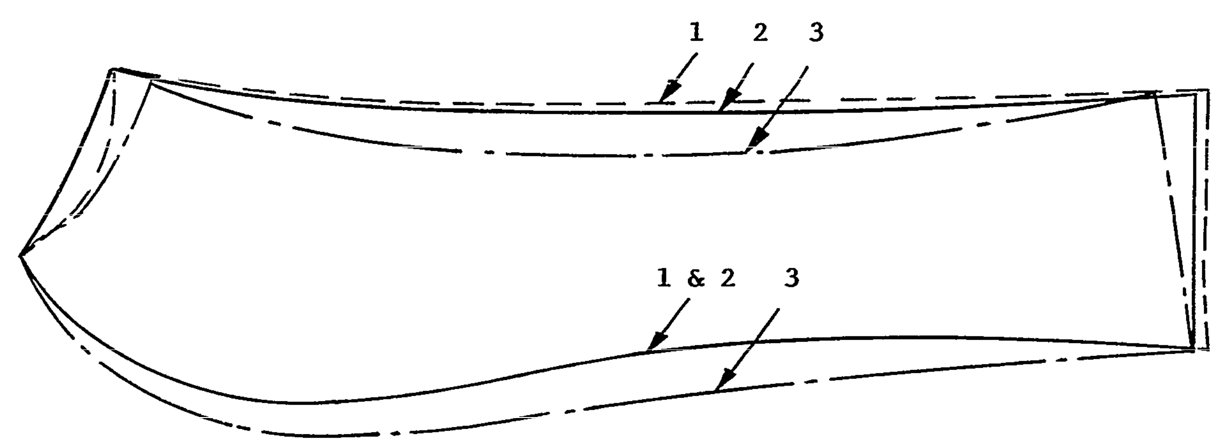


Figure 10 Test Case 5 Developed Plate Outlines

can be improved by dividing the complex shell plate into a number of smaller plates.

Recommendations

It is recommended that:

A study be undertaken of shipbuilding forming methods and the application of accuracy control to improve shell plate forming accuracy and consistency be undertaken.

A study be undertaken to develop ways to use advanced measuring devices, such as laser theodilites, for the checking and control of shaped shell plate forming.

Shipbuilders and CAL developers work together to develop new and improved computer developed data to assist shell plate forming operators to attain better accuracy and consistency.

ACKNOWLEDGEMENTS

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REFERENCES

1. M. Yuzaki & Y. Okurnato, “An Approach to a New Ship Production System Based on Advanced Accuracy Control,” NSRP 1992 Ship Production Symposium.
2. Avondale “Shipbuilding Technology Transfer - Design Engineering for Zone Outfitting” for NSRP, 1982.
3. Personal letter from NASSCO to T. Lamb discussing this study.
4. G. Southern “Work Content Estimating horn a Ship Steelwork Data Base,” RINA 1980.
5. P.D. Forrest & M.N. Parker, “Steelwork Design Using Computer Graphics,” RINA Spring Meeting, 1982.
6. S. Arase, et al, “CAD/CAM System for Ship Hull Structure,” 4th International Marine Systems Design Conference, 1991.

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Comparative Design of Orthogonally Stiffened Plates for Production and Structural Integrity

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ABSTRACT

Five configurations of orthogonally stiffened plates are studied to find structurally feasible cost optimal structures. First, size optimization is performed, with plate thickness and standardized beam cross section as discrete design variables. Total cost – including weight and work content - is used as an optimization criterion. Constraints include secondary/tertiary stress limits computed by Finite Element Analysis (FEA), three modes of buckling instability due to primary stresses, and producibility constraints dictated by standardization. The cost effect of structural volume due to cargo capacity loss is assessed. Next, shape optimization is performed to improve the optimal plates obtained by size optimization. A third discrete design variable - the stiffener spacing - is introduced. One weight, one work content, and one total cost optimum are identified for four of the five configurations. The overall best design and the opposite effects that variation of weight and work content have on the stiffened panel shape are discussed

NOMENCLATURE

A_3, A_5	cross section areas of stiffened plates 3 and 5
CERW	Cost Equivalent Relative Weight
C_3, C_5	material cost for stiffened plates 3 and 5
DOF(s)	degree(s) of freedom
D_x / D_Y	plate rigidity in x/y direction
D_{xy}	plate torsional rigidity in xy plane
E	modulus of elasticity of isotropic material
Ex/Ey	modulus of elasticity of orthotropic material in x/y direction
FE(M/A)	Finite Element (Method/Analysis)
G / G_{XY}	shear modulus of isotropic/orthotropic material
K	ratio of labor rate to material rate
N	life of ship in years
NCD	Net Difference in Cost
r	rate of return adjusted for time value of money
R	freight rate per cargo tonne
t	plate thickness
z	distance form the middle plane of the plate to the mean neutral surface of the 6_x stresses

Greek Symbols

AQ	loss in carrying capacity per hip
n	an effficiency factor to account for costs of additional cargo capacity
nt	number of trips per year at full load capacity
V	Poisson's ratio of isotropic material
Vx/Vy	Poisson's ratio of orthotropic material in x/y direction
6a/6y	allowable/yield stress

INTRODUCTION

Orthogonally stiffened plates constitute as much as 50% of steel hull structural elements and dominate the total cost and production time. Consequently, their structural integrity and total cost - including material and production cost – must be analyzed carefully in order to produce the best design. Shipyard practice has established several widely accepted configurations of stiffened plates. Winkle and Baird (1) identified five conventional configurations by surveying shipyards. Even though shipyards assessed those designs as structurally equivalent discussers (1) pointed out that this was not the case. The authors of this paper have shown by Finite Element Analysis (2,3) that in four of those five configurations (Figures 1-5) the maximum secondary and tertiary stresses exceed their limit set at 75.8 MPa (11000 psi).

To rationalize the comparison of the five stiffened plate configurations, structurally equivalent designs are identified, and an optimum is found for each

configuration. In the first section of this paper, structural equivalence is established by setting a common upper stress limit of 75.8 MPa (11000 psi) for the secondary and tertiary bending stresses. The remaining stress to reach the allowable limit of 206.9 MPa (30000 psi) – yield stress of 248.2 MPa (36000 psi) reduced by a 20% safety factor – is considered as the primary stress limit, and used as the lower limit for critical buckling stress, σ_{cr}. In the second section, a total cost model for stiffened plates is suggested, using the CERW (Cost Equivalent Relative Weight) method introduced by Moe and Lund (4). Production algorithms are developed to compute the total number of man-hours needed to fabricate each stiffened plate. In the third section, the structurally equivalent cost optimal design is calculated for each configuration. Basic geometric characteristics of each configuration are preserved in the (size) optimization process. In the fourth section, the five size optimal and structurally equivalent stiffened plates are compared on the basis of weight, fabrication and total cost. In the fifth section, the effect of the cargo carrying capacity on the lifetime cost of stiffened plates 3 and 5 is added. Finally, shape optimization is performed. The weight, work content, and relative weight optima are found for stiffened plates 1,2,4, and 5. Three discrete design variables – the stiffener spacing, the thickness of the plate, and the size of the stiffeners – are used in the optimization process. All optimal configurations considered are structurally equivalent. The cost optimal stiffened plate 3 found by size optimization cannot be subjected to shape optimization because certain geometric constraints make its shape unique.

STRUCTURAL ANALYSIS OF FIVE STIFFENED PLATE CONFIGURATIONS

Structural Equivalence

The five stiffened plates (Figures 1-5) which are studied in this section are all 10.7m (31.5 ft) long by 9.5m (31.17 ft) wide and constructed entirely of mild steel. They are loaded by a hydrostatic pressure due to 3m (9.84 ft) of water head. The boundary conditions are taken in such a way as to represent actual ship conditions. In general, the keel and longitudinals are continuous through the transverse bulkhead, and conditions are symmetric with respect to the bulkhead; thus the longitudinal members are assumed to be fixed at the bulkhead. In general, side framing is less stiff than bottom transverse members so that transverse members may be considered simply supported at a ship's side. The stresses occurring in marine structures are divided into three categories, primary, secondary, and tertiary stresses. A complete FE model of each stiffened plate is used for calculation of the secondary and tertiary stresses. So, for those stresses an upper limit has to be defined (based on available data and engineering judgment) which leaves adequate stress margin for the primary stresses which are the most important stresses in marine structures. Primary stresses can cause buckling of ship panels. Those stresses are not calculated in this work because they are application specific; that is they depend on the size, weight distribution, and midship section of the ship. In this paper, by considering the strength properties of the steel σ_y = 248.2 MPa (36000 psi) and a safety factor of 20%, a limit of 75.8 MPa (11000 psi) is chosen as an upper limit for secondary and tertiary stresses. Thus, a configuration will be acceptable if and only if the combined secondary and tertiary stresses are equal to or less than 75.8 MPa (11000 psi), and the remaining stress margin to reach 206.9 MPa (30000 psi) – allowed for the primary stresses – does not cause buckling. If the critical buckling stress of a configuration is less than the primary stress margin, then the failure mode is the buckling mode. So, the equivalence of strength is based on the two loading conditions and the five failure modes (1, 11) listed below:

Loadings:

1. In-plane load due to primary stresses
2. Lateral load due to secondary and tertiary stresses

Failure modes:

1. Plate bending due to lateral load (secondary and tertiary stresses)
2. Stiffener bending due to lateral load (secondary and tertiary stresses)
3. Overall stiffened plate buckling due to primary in-plane load
4. Stiffener tripping due to primary in-plane load
5. Plate buckling due to primary in-plane load

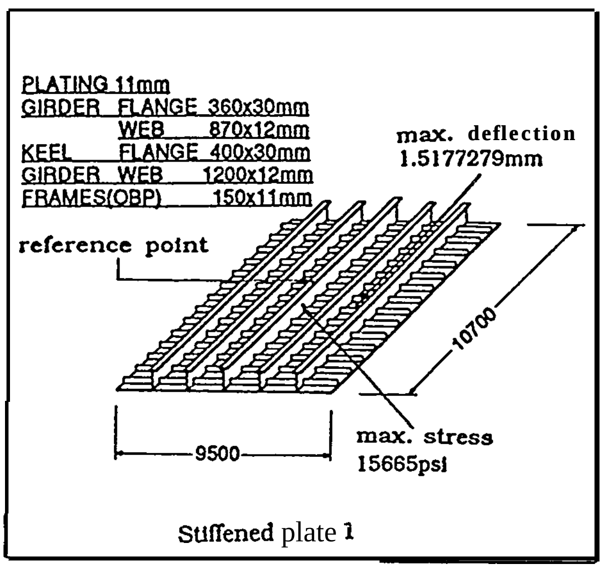


Figure 1. Characteristics of stiffened plate 1 (modified from ref. 1)

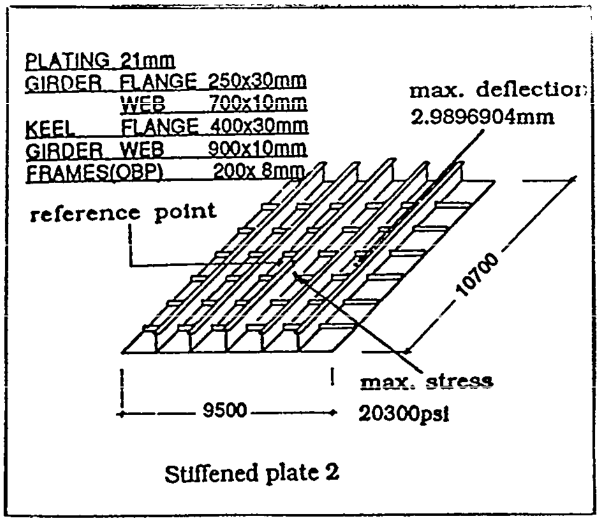


Figure 2. Characteristics of stiffened plate 2 (modified from ref. 1)

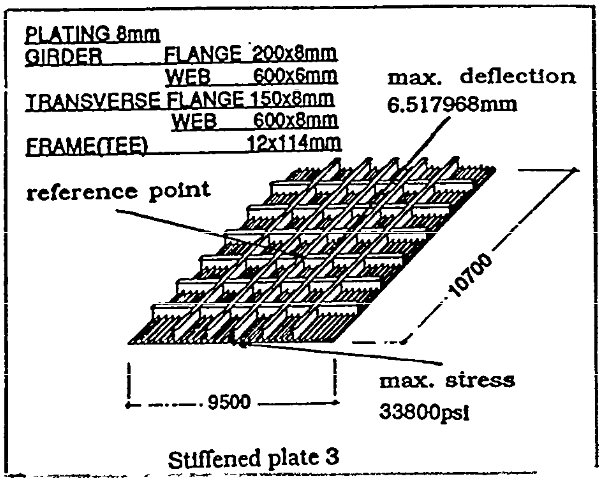


Figure 3. Characteristics of stiffened plate 3 (modified from ref. 1)

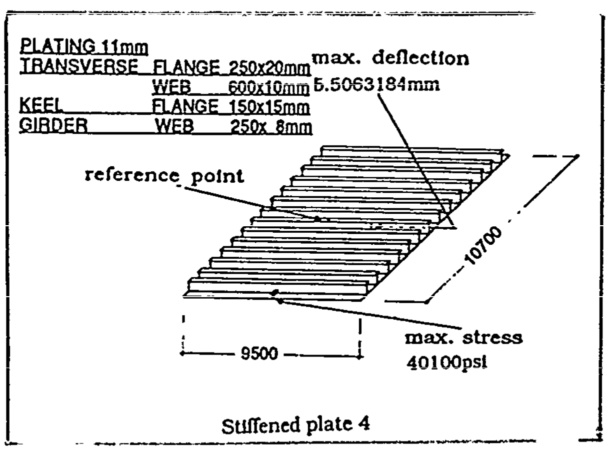


Figure 4. Characteristics of stiffened plate 4 (modified from ref. 1)

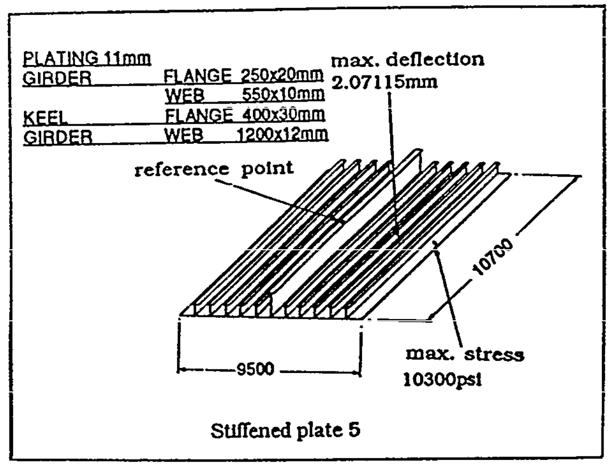


Figure 5. Characteristics of stiffened plate 5 (modified from ref. 1)

Secondary and Tertiary Stress Analysis

Three structural methods for calculation of secondary and tertiary stresses in stiffened plates by FEA are used in this paper: (i) a complete FE model, (ii) a two-dimensional grillage using effective breadth (equivalent stiffness concept) (5), (iii) orthotropic plate theory (6, 7). These three methods imply the use of a computer program capable of solving structural problems by the FE method (8).

The complete finite element model method and the method of effective breadth are used for configurations 1, 2, 4, and 5. The complete finite element model method and the method of orthotropic theory are used for configuration 3. Although only the complete FE model method is used for calculation of the secondary and tertiary stresses, the other two methods are applied in order to establish confidence in the FEA results (deflection) of the complete model by making comparisons to FEA results (deflection) using the other two methods, and to identify the best among these three methods by assessing the computational accuracy as a function of the number of DOFs and the required CPU time.

FEA of complete model: For the complete FEM model, quadrilateral plate and beam elements are used for the modeling of plates and stiffeners, respectively. The nodal points are placed at the middle plane of the plate elements. The beam element neutral axis is not on the plate neutral axis. The resulting additional stiffness is taken into account by using the offset option of the FEA program (8). Continuity of adjacent elements is simulated through the boundary conditions. The uniformly distributed load caused by a 3m (9.84 ft) hydrostatic pressure is applied directly on the plate element nodes.

FEA using the effective breadth method: In the 2-dimensional finite element grillage approach for

analyzing an orthogonally stiffened plate, the structure is converted to an equivalent grid of beams with neutral axes on the same plane. The stiffness of these beams include the corresponding equivalent plating. There are two different definitions of effective breadth based on two different concepts. The first is the breadth of the plate which – when used in calculating the moment of inertia of a section - gives the correct uniform stress at the junction of the web and the flange, using simple beam theory (9). Thus, it allows for the shear lag effect due to transmission of the lateral load to the web of a beam, and then to the flange of the beam by means of shear in the plane of the flange. The second concept – which is adopted in this paper-is the effective breadth of the plate which is independent of the applied load, and corrects the beam properties to produce a deflection that is nearly equal to that of the actual structure (5, 10).

FEA using orthotropic plate theory: Orthotropic theory replaces the plate and stiffeners with an equivalent orthotropic homogeneous plate of constant thickness. This plate has dtiferent rigidity properties in the two orthogonal directions corresponding to the stiffener directions. Thus, the orthotropic plate cannot be equivalent to the actual structure in every respect (6, 7). Equivalence may be based on either the deflection or one of the strain components at some plate point. The mean difference in deflections of the actual and equivalent plates maybe used for that purpose.

Initially, the rigidities of the equivalent orthotropic plate are calculated horn the following formulas:

$$D_x = \frac{Et^3}{12(1-\nu^2)} + \frac{Etz^2}{(1-\nu^2)} + \frac{EI_x}{s} \quad , \qquad (1)$$

$$D_y = \frac{E[h(y)]^3}{12(1-\nu^2)} \quad , \qquad (2)$$

$$D_{xy} = \frac{G}{6}\left(\frac{dh^3}{s}\right) \quad , \qquad (3)$$

where the rigidity in the x-direction (longitudinal), D_x, is the summation of the rigidity of the plate (fust term), plus the rigidity of the frames in the x-direction due to their offset with respect to the middle plane of the plate (second term), plus the rigidity of the repeating section in the x- direction (third term). The rigidity in the y-direction (transverse), D_y, is produced from equation (2) where the plate thickness t was replaced by h(y), the total thickness of the plate-stiffener combination subject to the limitation mentioned in reference (7).

The relations between the rigidities of the equivalent orthotropic plate and the elastic moduli E_x, EY ‘ ‘XY for the orthotropic plate are given by equations (4)-(6)

$$D_x = \frac{E_x t^3}{12(1-\nu_x \nu_y)} \quad , \qquad (4)$$

$$D_y = \frac{E_y t^3}{12(1-\nu_x \nu_y)} \quad , \qquad (5)$$

$$D_{xy} = \frac{G_{xy} t^3}{12} \quad . \qquad (6)$$

The rigidities for the orthotropic plate are derived based on equivalence of strain energy (7).

Buckling Analysis due to Primary Stresses

In this section, the buckling calculations are shown for the five stiffened plates. All the calculations are conservative and are based on the theory described in reference (11).

Stiffened Plates 1 and 2: These plates are stiffened both longitudinally and transversely. First, a check must be performed to find whether the transverse stiffeners have enough rigidity to provide nearly unreflecting supports to the longitudinal stiffeners. If the transverse stiffeners are not rigid enough, the panel may undergo gross panel buckling, in which case the transverse stiffeners buckle with the longitudinal. On the other hand, if the transverse stiffeners are sufficiently rigid, the stiffened plate between them is a simply supported longitudinally stiffened plate, and can be analyzed by the methods used for stiffened plate 5 below. For stiffened plates 1 and 2, it was found that the transverse stiffeners do not provide unreflecting supports. The minimum transverse rigidity ratio 7_y/7X to prevent gross panel buckling is :

$$\frac{\gamma_y}{\gamma_x} = \frac{B^4}{\pi^2 C a^4}\left(1+\frac{1}{p}\right) \quad , \qquad (7)$$

where y_y = E1y/Da, Y_x = EIX/Db ; a,b are the transverse and longitudinal spacings, respectively; D is the plate rigidity; C = $0.25+2JK^3$, where K is the number of longitudinal subpanels: L and B are the length and width of the stiffened plates and p is the number of longitudinal stiffeners.

Because of the small rigidity of the transverse stiffeners,, the gross panel buckling is checked. The two stiffened plates are idealized as orthotropic plates by “smting” the bending rigidity of the stiffeners over the region of the plating. The critical gross buckling stress is:

$$(\sigma_{ax})_{cr,gp} = k_0 \frac{\pi^2 (D_x D_y)^{1/2}}{B^2 \left(t + \frac{A_x}{B}\right)} \quad , \tag{8}$$

where ko=(m2/p2)+(2Hl(D.DY)V2 ~+(P2/m2) * H i the toksional rigidity of the orthotropic plate, $\rho = \left(L/B(D_y/D_x)^{1/4}\right)$ is the virtual aspect ratio, m isthe integer nearest o p ,t is the thickness of the plate, and Ax is the area of each longitufinal stiffener. The above orthotropic theory approach can be used only when the number of transverse stiffeners is large. For a small number of transverse stiffeners the orthotropic plate approach is not appropriate. In that case, the transverse stiffeners are neglected (conservative approach) and configurations 1 and 2 are examined as longitudinally stiffened plates, as in the case of stiffened plate 5.

Stiffened Plate 4: In this case, it is also found that the transverse stiffeners do not provide unreflecting supports. For this reason, the strength of the snong longitudinal stiffener in buckling and tripping is examined first. It is found that this stiffener has a very large critical buckling and tripping point. For that reason, it is assumed that it provides a simple support to the transverse stiffeners at the middle. Thus, only half of the stiffened plate is examined.

For a large number of transverse stiffeners, the orthotropic approach is used to compute the critical gross panel buckling stress. The rigidity in the longitudinal direction is taken equal to the rigidity of the plate only. For a small number of transverse stiffeners, the critical buckling point of the plate between the transveme stiffeners is computed w

$$(\sigma_{pl})_{cr} = k \frac{\pi^2 D}{b^2 t} \quad , \tag{9}$$

where k is the buckling coefficient depending on the boundary conditions and the aspect ratio of the plate. Stiffened plate 3 was not examined, because based on the discussion in reference (l), this stiffened plate is at least twice as strong as stiffened plate 4 which has been already examined.

Stiffened Plate 5: This is a longitudinally stiffened plate. So, it has to be ensured that: i) Overall buckling (stiffeners buckle along with the plating) does not precede plate buckling, and ii) the torsional rigidity is large enough to prevent local stiffener buckling (tripping). For the overall buckling, the critical buckling stress for a simply supported plate with stiffeners is:

$$(\sigma_a)_{cr} = \frac{\pi^2 E}{\left(\frac{L}{\rho}\right)^2_{eq}} \quad , \tag{1o}$$

where L/p is the slenderness ratio of the stiffener together with an effective width b of the plate, P² = (lx)/(% + bt), AX is the cross-sectional area of the stiffener only, and Ix is the moment of inertia of the stiffener with an effective width b of the plate. **Also, it has to be ensured that $(\sigma_a)_{cr} > (\sigma_{pl})_{cr}$ so** that the overall buckling does not precede plate buckling. A simple check for tripping of the longitudinal stiffeners can be performed by the following formula:

$$(\sigma_{aT})_{cr} = \frac{\pi^2 E}{12 + 4\frac{A_w}{A_f}} \left(\frac{b_f}{a}\right)^2 \quad , \tag{11}$$

where A_w and Af are the areas of the web and flange respectively, and bf is the width of the flange.

COST MODELING OF STIFFENED PLATE

Production Algorithms

The data used for the development of tbe production task algorithms (Tables I-V) are taken from references (1, 12, 13, 14, 15). The man-hours are obtained by traditional work study methods corresponding to performance applied to an efficiency of 1007o, and do not allow for normal periods of rest, environmental, and psychological effects of carrying out the task. For this reason, additional operation factors (1.6 for welding [13], 1.15 for cutting, grinding, blasting and painting [13, 14]) are included. The construction algorithms also include man-hours for preparation of the welding, cutting, grinding, blasting and painting machines, layout and pitching of the plates, transportation

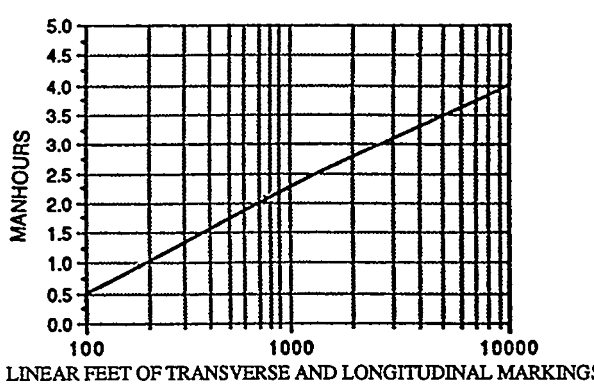


Figure 6. Time for marking (15)

jobs, marking of the panel (Figure 6), fitting and tackingof the stiffeners, etc. The construction sequence includes the following five steps described in Tables I - V, respectively (i) Flat panel sub-assembly, (ii) Flat panel marking, (iii) Stiffeners assembly and fitting to the panel, (iv) Welding of the stiffeners to the panel, and (v) Sandblasting and painting (with epoxy primer) of the panel.

Finally, the layout time calculation is based on the following

Total Layout Time = Setup Time+ Marking time,

Setup Time = 1.072 Man-hours,where the marking time is given in Figure 6.

Total Cost Modeling

In this section, the weight/cost comparison of the five stiffened plates is performed. It is assumed that the material rates are equal for all parts of the designs under consideration. The variable cost equation is the one used in reference (1}

Variable cost = (material weight* material rate)+ (man-hours * labor rate). (12)

The variable cost can be normalized to a Cost

Equivalent Relative Weight (CERW) (4) by dividing through by the material rate as follows

CERW (tome)= (material weight) (tonne)+ (K * man-hours) (tonne), (13)

where the normalizing factor K is

$$K = \frac{\text{labor rate}}{\text{material rate}} \left(\frac{\text{cost/manhour}}{\text{cost /tonne}} \text{ or } \frac{\text{tonne}}{\text{manhour}} \right) \quad (14)$$

This formulation is unique because it makes possible studying of the effkct of varying K, and can be applied to different areas of the world. Choosing a suitable

SEQUE.	ACTIVITY	OBJECT	MAN-HOURS (ref. 13 or as shown)	APPLIED PER
1	set-up	CM-45 portable burning machine	0.243	plate
2	preheat	plate	f_1(plate thk.,bevel ang)	plate
3a	burn (straight)	plate	f_2(plate thk.)	burning length
*3b	burn (bevel)	plate	f_3(plate thk.,bevel ang)	burning length
*3c	turn	plate	0.5 (1)	job
*3d	burn (bevel)	plate	f_3(plate thk.,bevel ang)	burning length
4	clear	shop floor	1.0 (1)	job
5	transport by pallet	plates	0.292 (1)	job
6	layout-pitch	plates	1.096	two plates
7	set-up	automatic submerged -arc welding job	0.213	job
8	set-up	automatic submerged -arc welding job	0.254	seam
9	butt weld	plate seams	f_4(plate thk.) (12)	welding length
10	weld pick-up	seams	0.029	seam
11	turn	panel	0.5 (1)	job
12	set-up	automatic submerged -arc welding job	0.254	seam
13	butt weld	plate seams	f_4(plate thk.) (12)	welding length
14	weld pick- up	seams	0.029	seam
15	transportation	chip/grind tools	0.134	shift
16	set-up and tear down	work area	0.189	seam (two sides)
17	chip/grind scars	plate seams	0.053	welding length
18	turn	panel	0.5	job
19	chip/grind scars	plate seams	0.053	welding length

* For plate thickness greater than 1.27 cm (0.5 in)

Table I: Flat panel sub-assembly

SEQUENCE	ACTIVITY	OBJECT	MAN-HOURS (ref. 15)	APPLIED PER
1	set-up	marking process	1.072	job
2	mark	panel	f_5 (total marking length, Fig. 3)	job

Table II: Flat panel marking

SEQUENCE	ACTIVITY	OBJECT	MAN-HOURS (ref. 13 or as shown)	APPLIED PER
1	set-up	hand torch	0.073	stiffener
2	preheat	web/flange	f_6 (plate thk.)	stiffener
3	burn	web/flange	f_7 (plate thk.)	cutting length
4	transport by pallet	webs/flanges	0.292 (1)	job
5	collect	plate lifting gear	0.252 (1)	job
6	position T-fashion	plate>8.33ft long	0.236 (1)	plate
7	align T-fashion	plate>8.33ft long	0.13 (1)	plate
8	fillet weld	flange to web	f_8 (web thk.) (12)	welding length
9	transportation	chipping/grinding tools	0.134	shift
10	set-up and tear down	work area	0.189	seam
11	grind edge	stiffeners	0.066	welding length
12	set-up	work place	0.154	per shift
13	fit and tack	frames	0.013	frame length
14	fit and tack	stiffeners	2.606	stiffener

Table III: Stiffeners assembly and fitting to panel

SEQUENCE	ACTIVITY	OBJECT	MAN-HOURS (ref. 13 or as shown)	APPLIED PER
1	Fillet weld	frames, stiffeners	f_9 (plate thk.) (12)	welding length
2	Fillet weld	penetrations	f_{10} (web thk.) (12)	welding length
3	transportation	chip/grind tools	0.134	shift
4	set-up and tear down	work area	0.189	seam
5	chip fitting and tacks	frames	0.113	frame
6	grind edges	frames	0.003	frame welding length
7	chip fitting and tacks	stiffeners	0.143	stiffener
8	grind edges	stiffeners	0.066	stiffener welding length
9	grind	penetrations	0.066	penetration welding length

Table IV: Welding of stiffeners to panel

SEQUENCE	ACTIVITY	OBJECT	MAN-HOURS (ref. 14)	APPLIED PER
1	set-up	blasting procedure	0.9919	job
2	blast	panel	f_{11}(panel area)	unit area
3	set-up	painting procedure	0.5168	job
4	paint	panel	f_{12}(panel area)	unit area

Table V: Flat panel sandblasting and painting

value for the normalizing factor K is critically important. This analysis considers the effects of K for two values, 0.05 and 0.1. Caution is recommended regarding the interpretation and units of factor K. This factor reflects the varying labor and material rates of the international construction business. The use of a higher K value represents high labor and overhead costs. Also, the units tome/man-hour do not imply any productivhy measure.

STRUCTURALLY EQUIVALENT COST OPTIMAL STIFFENED PLATES

For the variation of the standardized beam cross sections, all 190 Bethlehem structural tees included in reference (16) and the 7 standardized beam cross sections given in reference (1) are considered. For the variation of the thickness of the plate, only integer numbers in millimeters are included in the analysis. The optimality criterion (objective function) in this section is the total cost of production and materials defined in the next section.

Optimal Sizing of Stiffened Plate 1

The strength analysis of stiffened plate 1 is performed first by a complete FEM model and then by the method of equivalent stiffness (effective breadth) with FEM. The geometric characteristics of the plate and the stiffeners are shown in Figure 1. Finite element models are prepared for both methods, and the variation of the deflection is observed at a reference point (only for the complete FEM method), as a function of the CPU time and the number of grid points (hence, the number of degrees of freedom) (2). Table VI shows the final choice for the characteristics of the complete FEM model for all 5 stiffened plates. It is found that the required number of grid points and degrees of freedom for the method of effective breadth are 430 and 1219, respectively. The CPU time was 220sec. Final results for the location and the numerical value of the maximum deflection, the maximum stress, and the location of the reference point for the complete FEM model are shown in Figure 1. Results for the location and the numerical vrdue of the maximum deflection for the method of effective breadth were derived in (2).

The maximum stress for the beams is equal to 108 MPa (15665 psi). From the definition of structural equivalence, it is concluded that this configuration is not acceptable. Also, it is found that the replacement of the transveme stiffeners with stiffeners of type WT8X13 (16) and the decrease of the plate thickness from 1 lmm to 5mm gives a configuration which has maximum stress 73.8 MPa (10700 psi) for the beams, and 41.4 MPa (6000 psi) for the plate. The longitudinal stiffeners of the original design (Figure 1) are optimal. Even though a small further decrease of the plate thickness is feasible (small stress in the plate), the thickness is not decreased because, (i) it is assumed that 5mm is the smallest acceptable thickness, and (ii) such change would result in increase of the beam stress to a level above the limit of 75.9 MPa (1 1000 psi). The optimally sized stiffened plate 1 which will be considered for comparison later (Table VII) has the same longitudinal stiffeners, plate thickness equal to 5mm (1.97 in), and WT8X13 as transverse stiffeners. The above configuration, for unchanged longitudinal stiffeners, is the optimum with respect to the total cost. It should be remembered that the geometry (number and spacing of the stiffeners) was left the same as in the initial configuration.

Optimal Sizing of Stiffened Plate 2

Similar strength analysis is performed for stiffened plate 2. Table VI shows the results of the deflection convergence process for the complete FEM model. The corresponding required number of grid points and degrees of freedom for convergence for the method of effective breadth are 295 and 741, respectively. The corresponding CPU time is 117.3 sec. Final results for the location and the numerical value of the maximum deflection, the maximum stress, and the location of the reference point for the complete FEM model are shown in Figure 2. Final results for the location and thenumerical value of the maximum deflection for the method of effective breadth were derived in (2).

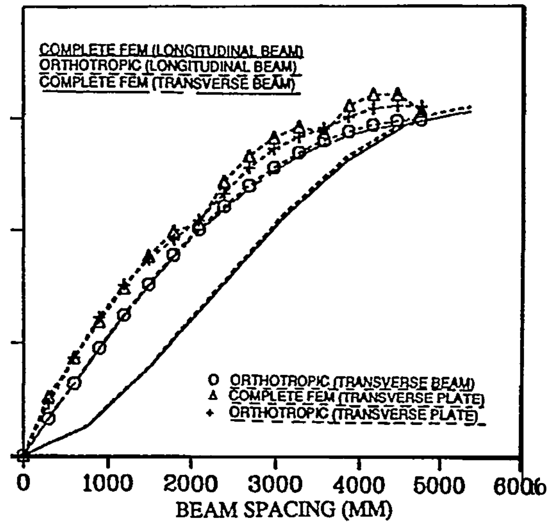
	Plate #1	Plate #2	Plate #3	Plate #4	Plate #5
Deflection (mm)	0.347	0.700	5.91	4.65	0.275
Number of grid points	775	724	975	969	1225
Number of DOFS	2059	1917	2483	2585	3289
CPu (see)	408.8	400.6	590.5	631.8	701.2

Table VE Convergence of reference point deflection for complete FEM models

The maximum stress for the beams is equal to 140 MPa (20300 psi), which implies that the above structure is not acceptable. It is found that replacement of the transverse stiffeners with the stiffeners of the type WT9X20 (16) and the decrease of the plate thickness from 21mm (8.27 in) to 13mm (5.12 in) produces the optimally sized plate 2, which has maximum stress 74.51 MPa (10805 psi) for the beams, and 61 MPa (8850 psi) for the plate. The longitudinal stiffeners of the original design (Figure 2) are optimal. The optimal stiffened plate 2 has the same geometry, the same longitudinal stiffeners, plate thickness equal to 13mm, and WT9X20 as transverse stiffeners. This configuration is actually the overall optimum with respect to the total cost, as shown in Table VII.

Optimal Sizing of Stiffened Plate 3

For the strength analysis of stiffened plate 3, the complete FEM model and the method of orthotropic plate theory are used. Table VI shows the results of the deflection convergence process for the complete FEM model. The corresponding number of grid points and degrees of freedom for the orthotropic theory FEM model are 975 and 2483, respectively. The CPU time is 576,3 sec. For the application of orthotropic theory, it is assumed that only the longitudinal frames are lumped with the plate to obtain the equivalent orthotropic plate. Final results for the location and the numerical value of the maximum deflection, the maximum stress, and the lccation of the reference point for the complete FEM method are shown in Figure 3. To compare the two methods, the deflection along (i) the middle stiffeners in both directions and (ii) the plate at the middle in the transverse direction were derived in (2). The strain energy ob@ned from the complete FEM model is 3.59 x 10^6Nt.mm (31,754 Ibf*ft). The result from the orthotropic theory is 3.5 x 10^6Nt.mm (30,958 ft-lbs). This result and Figure 7 show that the two methods of analysis produce similar results. The maximum stress for the beams is found to be equal to 233 MPa (33800 psi) which proves that the above shucture is not acceptable. Replacement of the longitudinal stiffeners (girders) with the stiffeners of the type: flange 250 x 30mm (9.84 x 1.18 in), web 700x 10mm (27.56 x 0.39 in); and reduction of the plate thickness from 8mm to 5mm produces the optimal sizing which has a maximum stress of 71 MPa (10300 psi) in the beams, and 30 MPa (4350 psi) in the plate. The longitudinal hues and the transverse stiffeners were found to be optimal. Thus, the optimum for stiffened plate 3 has the same geometry, and the same transverse stiffeners and longitudinal frames as the original design in Figure 3; plate thickness 5mm, and longitudinal girders with flange 250 x 30mm (9.84 x 1.18 in) and web 700 x 10mm (27.56x 0.39 in).



ure 7. Deflection comparison of complete FE model to FEM using orthotropic theory modeling for stiffened plate 3.

ıal Sizing of Stiffened Plate 4

For the strength analysis of stiffened plate 4, the complete FEM model and the method of equivalent stiffness (effective breadth) are used. Table VI shows the deflection convergence process for the complete FEM model. The last column describes the selected model. The corresponding number of grid points and degrees of freedom for the method of effective breadth are 505 and 1543, respectively. The CPU time is 235.7. The final results for the location and the numerical value of the maximum deflection, the maximum stress, and the location of the reference point for the complete FEM model are shown in Figure 4. Final results for the location and the numerical value

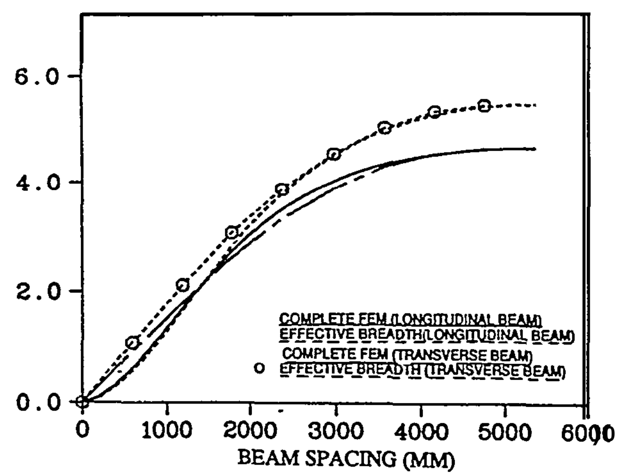


Figure 8. Deflection comparison of complete FE model to FEM using effective breadth

of the maximum deflection for the method of effective breadth were derived in (2). Figure 8 shows that the two methods of analysis produce similar results.

The maximum stress for the beams is equal to 276.5 MPa (40100 psi), which is much higher than the 75.9 MPa (11000 psi) limit. Replacement of the longitudinal stiffener with the stiffener of the type: flange 400 x 30mm (15.75 x 1.18 in) and web 1200x 12mm (47.24 x 0.47 in); decrease of the plate thickness horn llmm (0.43 in) to 8mm (0.32 in); and replacement of the transverse stiffeners with stiffeners of the type: flange 250 x 20mm (9.84 x 0.79 in) and web 550 x 10mm (21.65 x 0.39 in), gives the optimally sized plate 4, which has a maximum stress of 74 MPa (10730 psi) in the beams, and 55.2 MPa (8000 psi) in the plate.

Optimal Sizing of Stiffened Plate 5

Similar strength analysis is performed for stiffened plate 5. Table VI shows the results of the deflection convergence process for the complete FE model. The required number of grid points and degrees of freedom for convergence for the method of effective breadth are also 1225 and 3289, respectively. This is so because the plate stiffness is simulated in the transverse direction by small transverse stiffeners having the same bending rigidity with the plate. The CPU time was reduced to 581.7 sec. The final results for the location and the numerical value of the maximum deflection, the maximum stress, and the location of the reference point for the complete FEM model are shown in Figure 5. Final results for the location and the numerical value of the maximum deflection for the method of effective breadth were derived in(2).

The maximum stress in the beams and plate was found to be equal to 65.5 MPa (9500 psi) and 71 MPa (10300 psi), respectively, so the structure is acceptable and optimum with respect to the total cost.

WEIGHT, FABRICATION, AND TOTAL COST COMPARISON OF THE FIVE OPTIMAL STRUCTURES

After replacing the initial stiffened plates shown in Figures 1-5 with structurally equivalent plates – which are also individually optimized from the total cost point of view - it is possible to proceed to a weight/cost comparison of the stiffened plates. Table VII presents the relevant results for the five structurally equivalent size-optimal stiffened plates.

Work content and cost equivalent relative weight vary inversely to the weight of these structures. Stiffened plate 3 is the lightest design, but it has the highest work content. Also, for K equal to 0.05 and 0.1, plate 3 has the highest relative weight (total cost). It is the lightest design because it has very thin plating and light longitudinal and transverse stiffeners. It has the highest work content because it has a large number of stiffeners, requiring a large number of man-hours for the cutting, marking, and welding.

Plates 1 and 2 are stiffened in two orthogonal directions. Stiffened plate 1 is lighter than stiffened plate 2 because it has thinner plating and lighter stiffeners, but it has a higher number of closely spaced transverse stiffeners with associated high work content. Also, plate 1 has higher relative weight (total cost) than plate 2 for both values of K . Plates 4 and 5 are stiffened primarily in one direction. Stiffened plate 5 is the heavier of the two (actually it is the heaviest of all the designs) but it has the lowest work content of the two (actually it has the lowest of all the designs). For K = 0.05, plate 5 has the second lowest relative weight and for K = 0.10 it has the lowest relative weight. Thus, if the labor rates are high enough, it is better to design heavy grillages with associated small work content. Plate 4 requires higher work content because it has a larger nurnbe;of transverse stiffeners.

DESIGN	WEIGHT tonnes	RELATIVE WORK CONTENT man-hours	CERW (tonnes) K = 0.05	K= 0.10
	14.7716	385.8854	34.0659	53.36
1	17.3951	260.388	30.4145	43.4339
3	14.1	425.4877	35.3	56.65
4	18.1929	308.7844	33.632	49.07
5	18.426	247.4517	30.798	43.171

Table VIE Comparison of the ‘five size-optimal stiffened plates

Discussion of reference (1) established that, based on experience, the weight difference between grillages similar to 1 and 3 has to be less than 10%. In Table VII, it is shown that the weight difference from the results obtained in this analysis is approximately 4.5%. Also, if the weight of the five stiffened plates is examined, after sorting them in ascending order, the maximum difference in weight betwem two consecutive designs is less than 15%, which represents an acceptable weight increase for equivalent structures in most ships.

EFFECT OF STRUCTURAL VOLUME ON THE LIFE TIME COST OF THE STRUCTURE

In this section, a relative cost comparison is made by adding the effects of the loss of cargo carrying capacity to the results tabulated in Table VII. Heavy designs have a smaller midship section, which results in reduced cargo carrying capacity over the lifetime of the designs. Specifically, plate 3, which is the lightest but most expensive design, is compared to plate 5, which is the heaviest and least expensive design. The cost modeling adopted for the total cost comparison of the two designs (3, 5) is the one used by Kriezis (17), modified to solve the problem addressed in this section. This model assumes that the difference between designs 3 and 5 is due only to the different material costs, the loss of cargo carrying capacity over the life of the ship of the heavier design (design 5), and the difference in fabrication man-hours for construction. Accordingly, the net cost difference is

$$NCD = \Delta_{\text{fabrication cost}} - \Delta_{\text{material cost}} - \Delta_{\text{carrying capacity cost}} \tag{15}$$

where,

$$\Delta_{\text{material cost}} = L\ (C_5 - C_3)\quad , \tag{16}$$

$$\Delta_{\text{carrying capacity cost}} = \sum_{i=1}^{N} \frac{\eta\, \Delta Q\, \eta_t\, R}{(1+r)^i}\quad , \tag{17}$$

$$\Delta Q = L\rho\ (A_5 - A_3)\quad . \tag{18}$$

The above model provides a reasonable estimate of the overall cost advantages and disadvantages of design 3 over design 5. Hence, it provides a designer with the information needed to design a particular vessel for minimum weight versus designing that vessel for minimum total cost.

The fabrication cost difference ix

$$\text{'fabrication cost} = \text{labor rate x (work content3 - work content5)}\ . \tag{19}$$

The values of the work content for the two designs are taken from Table VII. A labor rate of $50/hour is used, which includes direct and overhead costs, and is a reasonable estimate for labor cost in the U.S.A. Substitution of those values in equation (19) results im

$$\text{'fabrication cost} = \$8{,}902.00\ . \tag{20}$$

For calculation of the carrying capacity cost difference, equations (3) and (4) are used. A maximum of 10 trips per year at full load capacity, and a ship life time of 20 years, are assumed. The freight rate per cargo tonne is $10/tonne. The rate of return – adjusted for time value of money - is assumed to be 15%, and the efficiency factor η , accounting for the cost of additional carrying capacity, is to be l.O(no costs). Finally, after calculating the cross section areas, and hence, AQ, we have:

$$\text{harrying capacity cost} = \$3{,}927.00\ . \tag{21}$$

For calculation of the material cost difference, the material cost data for plates in standard production are taken from the information given in reference (17). This results in:

$$\text{material cost} = \$2{,}470.00\ . \tag{22}$$

Summarizing, design 3 is $8,902 more expensive in construction, $3,927 less expensive in cargo carrying capacity, and $2,470 less expensive in materials, than design 5.

Substitution of the values for the cost differences into equation (15) yields that design 3 is $2,505 more expensive than design 5. A ship constructed by using tsventy panels of type 3 is $50,100 more expensive than a ship which has been constructed by using twenty designs of type 5. From the above simple but reasonable study, it can be concluded that the advantages of a minimum weight design, which are the low material cost and the higher cargo carrying capacity, cannot compensate for the disadvantage of high fabrication cost. So, minimizing the work content becomes the dominant factor in selecting the overall size optimum.

Although the above anrdysis does not intend to cover in detail all the variables which influence the engineering economy of a ship, a naval architect must know how to make economic studies, and how to estimate future costs of designing, building and operating ships. Hence, the conditions under which the result can be changed must be studied. That is, under what conditions may design 3 be better than design 5. For this purpose, a sensitivity analysis of the various economic parameters is performed. By making the assumption that the material and the fabrication costs do not change the most important economic parameter which can influence the remaining carrying cargo capacity costs, and hence the final result, is the rate of return adjusted for the time value of money r . This parameter includes the effect of inflation and the reward of investing or borrowing money (interest) (18). When parameter r becomes smaller, the ship which has been constructed with the panel designs of type 5 becomes more expensive regarding the cargo carrying capacity cost. Thus, there is a crossover point where a ship constructed using the panel designs of type 5 becomes more expensive overall. By performing sensitivity

analysis with respect to parameter r, it can be shown (Figure 9) that for r smaller than 7.55% design 3 becomes overall better than design 5; that is, the maximum work content design becomes the optimum one.

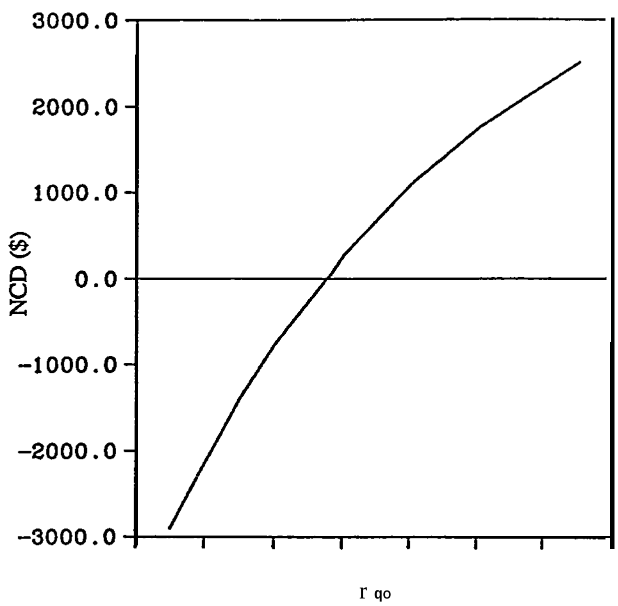


Figure 9. Net difference in cost (NCD) versus time value of money (r)

STRUCTURALLY EQUIVALENT SHAPE-OPTIMAL STIFFENED PLATES

In this section, for four out of the five stiffened plates (1, 2,4, 5), the weight, fabrication and total cost are computed for discrete values of plate thickness, standardized beam cross section, and discrete beam spacing. For stiffened plates 1 and 2 ONLY the spacing of the transverse frames is varied, because the maximum stress occurs in these beams (Figures 1, 2). Variation of the stiffener spacing is performed in such a way that salient geometric features regarding the arrangement of stiffeners are preserved. For example, in stiffened plate 1, only an even number of transverse stiffeners is considered. The location of these stiffeners is such that the number of the stiffeners is equal to the number of the spaces between them, as in the initial configuration of Figure 1. Note that end spaces are half the width of the other spaces. With regard to the variation of the thiclmess of the plate, it is assumed again that the minimum plate thickness is 5mm. Further, only standard plate thickness is considered. That is, the plate thickness can only bean integer number in millimeters. With regard to the size of the stiffeners, all 190 Bethlehem structural tees, (16) and the 7 structural tees given in reference (1) are considered for the variation of the size of the stiffeners for all configurations. The Bethlehem catalog refers to standard structural tees that are used in the United States.

Optimal Shape of Configuration 1

For plate 1, the optimum results for three different objective functions (weight, work content, total cost) and for discrete beam spacing are presented in Table VIII. In most cases, the three optima are identical. When this is not the case, a line is repeated and the appropriate optimum is shown as in the case of 16 and 2 stiffeners. All of Tables VIII-XI are constructed in that way. Graphs for the optimum configurations in Table ~ are shown in Figme 10.

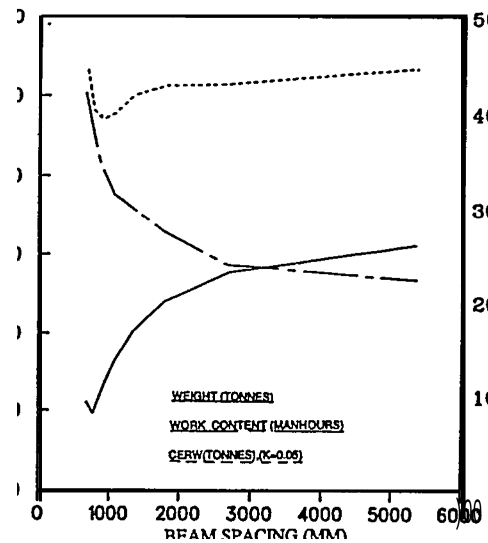


Figure 10. Optimum stiffened plate 1 for discrete beam spacing

The weight of stiffened plate 1 increases as the stiffener spacing increases. This happens because as the beam spacing increases – although the number of the transverse stiffeners being used is smaller – the size of the stiffeners, and hence their weight, is increased in order to resist the applied load. Most important, as the beam spacing increases, the thickness of the plate must be increased, and the plate accounts for most of the weight in these designs. The rate of increase of the weight, however, becomes smaller for larger stiffener spacings because the requirement for thicker plate is not very demanding for large beam spacing. So the reduction in the number of the stiffeners can compensate for a portion of the increase of the weight due to the small increase of the thickness of the plate for larger beam spacings. These are two main reasons that slightly thicker plate is needed for larger beam spacings.

First, Plate 1 is orthogonally stiffened. In Table VIII, it is shown that for transverse beam spacings up

to 1337.5mm (52.66 in), the need for plate thickness was increasing. Having in mind that the distance between the longitudinal stiffeners is fixed (1583.3mm = 62,33 in), and the St. Venant principle (the load follows the stiffer path), it can be concluded that the load will follow the longitudinal direction for transverse beam spacings up to 1337.5mm. So there is need for increased plate thickness. For transverse beam spacings greater than 1337.5mm Table VIII shows that the required increase in plate thickness is constant and equal to 3mm (0.12 in). This happens because for these beam spacings the load will follow the transverse direction which remains constant and equal to 15!33.3mm.

Second, the results in Table VIII are based on discrete optimization, and were produced subject to the limitations of standardization. If the optimization was continuous, the plate thickness needed to go from a spacing of 891.67mm (35.11 in) to a spacing of 1070mm (42.13 in) would be slightly more than 2mm (0.08 in); and not 3mm as the table shows. Therefore, the need for larger plate thickness is not incremental and equal to 3mm for beam spacings larger than 891.67mm.

The total panel weight for beam spacing of 668.75mm (26.33 in) is greater than the weight for beam spacing of 764.28mm (30.09 in). This seems to be contradictory with the rest of the curve. This contradiction exists because of the assumption that it is not possible to use plate with thickness less than 5mm, and also because there is no WT8 type of standard tee sections smaller than WT8X13. The curves of Figure 10 would be slightly different if the optimization was continuous. Finally, the optimum weight combination is the one with beam spacing of 764.28mm, light plating (5mm = 0.2 in), and 14 light transverse stiffenem (wT8x13).

An examination of the work content to spacing relationship shows that the work content decreases as the beam spacing increases because the number of transverses decreases. So, in most cases, the number of job operations decreases. The only job that requires higher man-hours is the cutting and welding of thicker plates as beam spacing increases. Actually, the work content curve becomes almost horizontal for larger beam spacings. This means that as the beam spacing increases, the increase in man-hours for cutting and butt welding of very thick plates can compensate for the decrease in man-hours for all the other jobs. Hence, the optimum work content desire is the one with b&rn spacing of 5350mm (216.63 in), thick plating

# OF TRANS, STIFF.	SPACING mm	TEE SECTION [16]	PLT. THK. mm	WEIGHT tonnes	OBJECTIVE F UNCTION WORK CONTENT man-hours	CERW tonnes	MAX. STRESS MPa
16	668.75	WT8X13	5	15.1	— —	36.41	65.03
16	668.75	WT6X15	5		421.31		71.03
14	764.28	WT8X13	5	14.77	385.88	34.065	73.78
12	891.67	WT8X15.5	7	16.25	345.6	33.53	71.99
10	1070	WT8X15.5	10	18.5	315.04	34.256	75.09
	1337.5	WT9X17.5	13	20.1	299.276	35.03	73.03
:	1783.33	WT9X17.5	16	21.95	273.456	35.6	73.03
4	2675	WTwc20	19	23.84	237.697	35.73	72.03
					221.995		72.03
2	5350	WTIO.5X22	22	25.59		36.7	71.03

Table VIIL Optimal configurations of stiffened plate 1

(22mm = 0.87 in), and only 2 heavy transverse stiffeners m=3j.

An examination of the total cost to spacing relationship shows that the optimum total cost combination is the one with beam spacing of 891.67mm, (35.11 in) light plating (7mm), and 12 transverse stiffeners (WT8X15.5). For beam spacings larger than 891.67mm, the curve shows that the total cost increases slightly but constantly as the beam spacing increases.

Finally, the above results show that the weight shape-optimum occurs for beam spacing which is smaller than the beam spacing of the total cost optimum.

Optimal Shape of Configuration 2

For plate 2, the optimum results for the three objective functions (weight, work content, total cost) and for discrete transverse spacing are presented in Table IX. Graphs for the optimum conilgumtions tabulated above are shown in Figure 11. This plate is cross stiffened, so it is expected that the behavior of the thee objective functions will be similar to the behavior of tbe corresponding functions for stiffened plate 1. The weight of the stiffened plate increases as the stiffener spacing increases. The same conclusions as for plate 1 apply for plate 2 for the weight to spacing relationship. Again, a sharp change in slope occurs for beam spacing

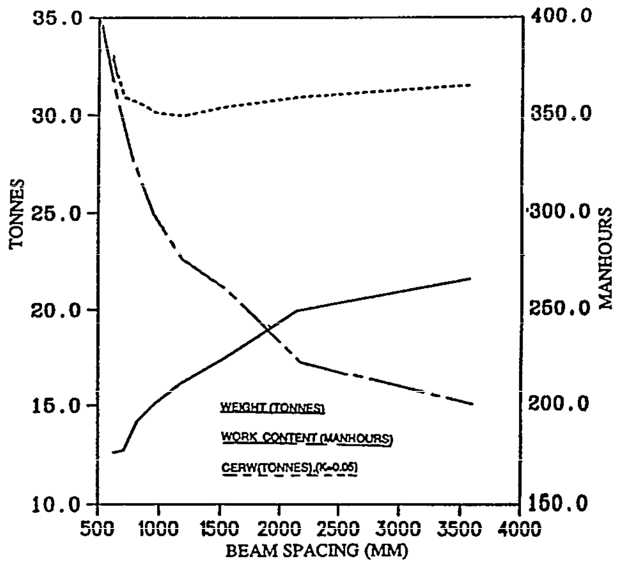


Figure 11. Optimum stiffened plate 2 for discrete beam spacing

of 713.3mm (28.08 in) because of the assumption that plate thickness of more than 5mm (0.2 in) should be used. The optimum weight combination is the one with beam spacing of 629.4mm, light plating (5mm) and 16 light transverse stiffeners (WT8X13).

The work content decreases as the beam spacing increases for the same reasons stated for plate 1. The optimum work content combination is the one with beam spacing of 3566.67mm (140.42 in), thick plating (20mm = 0.79 in) and two heavy transverse stiffeners (WT10.5X22).

The optimum total cost combination is the one with a beam spacing of 1188.9mm (46.81 in), light plating (11mm) and 8 transverse stiffeners (WT9X17.5). For beam spacings larger than 1188.9mm the curve shows that the total cost increases slightly but approximately linearly.

Finally, from the above results show that the weight optimum occurs for beam spacing which is smaller than the beam spacing of the total cost optimum.

Optimal Shape of Configuration 4

For stiffened plate 4, the optimum results for the three objective functions (weight, work content, total cost) and for discrete transverse beam spacing are presented in Table X.

Graphs for the optimum configurations tabulated above are shown in Figure 12. This plate is stiffened primarily in the transverse direction, so it is expected that the behavior of the three objective functions will be different from the behavior of the corresponding functions for plates 1 and 2.

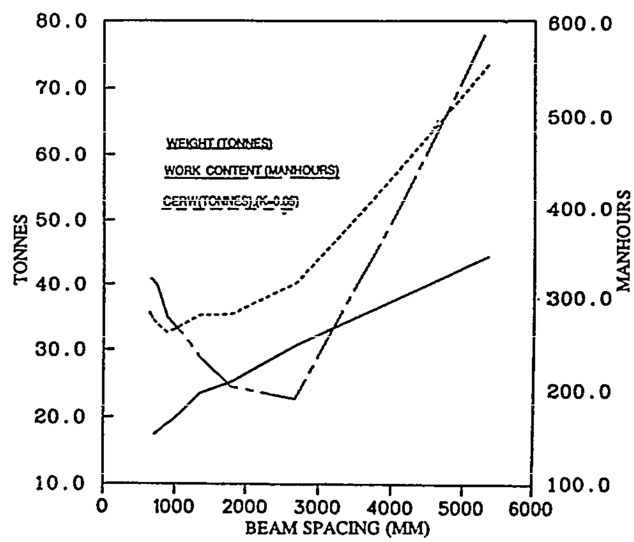


Figure 12. Optimum stiffened plate 4 for discrete beam spacing

# OF TRANSVERSE STIFFENERS	SPACING mm	TEE SECTION [16]	PLT. THK. mm	OBJECTIVE FUNCTION: WEIGHT tonnes	WORK CONTENT man-hours	CERW tonnes	MAX. STRESS MPa
16	629.4	WT8X13	5	12.58	397.546	32.45	71.58
14	713.3	WT8X15.5	5	12.688	364.314	30.9	72.61
12	823	WT8X18	7	14.1624	329.827	30.65	74.34
10	972.7	WT9X17.5	9	15.123	300.16	30.45	73.10
8	1188.9	WT9X17.5	11	16.1526	276.517	29.97	75.16
6	1528.57	WT9X20	13	17.395	260.38	30.41	74.51
4	2140	WT10.5X22	17	19.927	——	30.96	73.44
4	2140	WT9X23	17	——	219.92	——	74.82
2	3566.67	WT10.5X22	20	21.58	198.13	31.489	75.03

Table IX: Optimal configurations for stiffened plate 2

# OF TRANSVERSE STIFFENERS	SPACING mm	TEE SECTION mm [1]	PLT. THK. mm	OBJECTIVE FUNCTION WEIGHT tonnes	WORK CONTENT man-hours	CERW tonnes	MAX. STRESS MPa
14	764.28	600X6-150X8	8	17.1	------	------	75.03
14	764.28	550X10-250X20	8	---	308.78	33.632	73.99
12	891.67	550X10-250X20	11	18.96	275.82	32.5	75.06
10	1070	550X10-250X20	15	20.47	261.18	33.53	74.03
8	1337.5	700X10-250X30	18	23.46	234.13	35.17	73.99
6	1783.33	700X10-250X30	23	25.16	202.08	35.32	79.03
4	2675	700X10-250X30	33	30.57	190.25	40.1	75.06
2	5350	1200X12-400X30	52	44.31	583.86	73.5	75.06

Table X: Optimal configurations for stiffened plate 4

The weight of the plate increases as the stiffener spacing increases. The rate of increase of the weight doesn't drop for larger stiffener spacings, as is the case of plates 1 and 2. The main reason is that plate 4 is unidirectionally stiffened, which means that the requirement for larger thickness of the plate is very demanding for large beam spacings. So, for a transverse beam spacing of 5350mm (2.06 in), the thickness of the plate must be 52mm (2.05 in), which is 19mm (0.75 in) greater than the required plate thickness for transverse beam spacing of 2675mm (105.3 in). In plates 1 and 2 the corresponding increase was only 3mm (0.12 in). The optimum weight combination is the one with beam spacing of 764.28mm (30.09 in), light plating (14mm = 0.55 in) and 14 light transverse stiffeners (web 600X6mm, flange 150X8mm).

For small transverse beam spacings, the work content decreases as in the cases of plates 1 and 2. The reduction in the number of transverse stiffeners afforded by increased spacing saves considerable time. The rate of the work content reduction, however, becomes smaller as the beam spacing increases, because the requirement for a thicker plate increases the number of man-hours for cutting and butt welding the plate. In fact, for transverse beam spacing greater than 2675mm (105.31 in), the objective function of work content increases significantly, because many man-hours are needed for cutting and multiple pass butt welding 52mm (2.05 in) thick plate needed for a beam spacing of 5350mm (210.6). So, for a large beam spacings the size of the stiffener has a small effect on the fabrication time of this stiffened plate. The optimum work content combination is the one with transverse beam spacing of 2675mm, 33mm (1.31) plate thickness, and transverse stiffeners of the type: web 700X10mm, flange 250X30mm.

The optimum total cost combination is the one with beam spacing of 891.67mm (35.11 in), light plating (11mm = 0.43) and 12 light transverse stiffeners (web 550X10mm, flange 250X20mm). Again, the total cost optimum occurs for a beam spacing which is larger than the beam spacing of the weight optimum.

Optimal Shape of Configuration 5

For plate 5, the optimum results for the three objective functions (weight, work content, total cost) and for discrete longitudinal beam spacing are presented in Table XI.

# OF TRANSVERSE STIFFENERS*	SPACING mm	TEE SECTION mm [1]	PLT. THK. mm	OBJECTIVE FUNCTION WEIGHT tonnes	WORK CONTENT man-hours	CERW tonnes	MAX. STRESS MPa
10	791.67	550X10-250X20	11	18.426	247.45	30.8	71.23
8	950	550X10-250X20	14	19.01	215.55	29.78	75.03
6	1187.5	700X10-250X30	16	20.73	192.39	30.34	75.03
4	1583.33	700X10-250X30	21	22.9	159.67	30.88	74.82
2	2375	870X12-360X30	30	27.64	133.65	34.3	73.03

*Does not include the middle longitudinal keel stiffener

Table XI: Optimal configurations for stiffened plate 5

Graphs for the optimum configurations tabulated above are shown in Figure 13. Plate 5 is a unidirectionally (longitudinally) stiffened plate, so the results are expected to be similar to the results obtained for plate 4. For this discrete shape optimization, the middle longitudinal keel stiffener was kept the same as shown in Figure 5 because the keel stiffener provides strength and acceptable stresses at the clamped ends of the other longitudinal stiffeners.

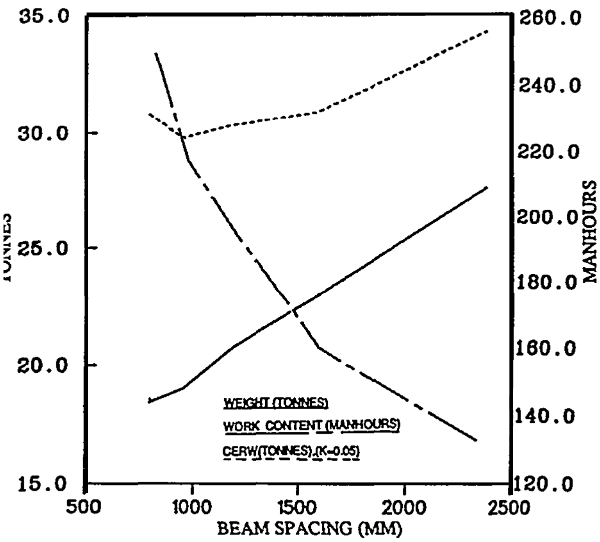


Figure 13. Optimum stiffened plate 5 for discrete beam spacing

The weight of the stiffened plate increases as the stiffener spacing increases, with approximately the same rate as the rate of the weight increase of plate 4. Thick plate is required for large beam spacings for the same reasons as those for plate 4. The optimum weight combination is the one with a beam spacing of 791.67mm (31.17 in), llmm (0.43 in) plating and 10 light longitudinal stiffeners (web 550X10mm, flange 250X20mm).

The work content decreases as the longitudinal beam spacing increases. The rate of the work content decrease becomes smaller for large beam spacings for the same reasons as those for plate 4. The optimum work content combination is the one with longitudinal beam spacing of 2375mm (93.50 in), 30 mm (1.18 in) plating and 2 heavy longitudinal stiffeners (web 870X12mm, flange 360X30mm).

Finally, the optimum total cost combination is the one with longitudinal beam spacing of 950mm (37.40 in), 14mm (0.55 in) plating and 8 light longitudinal stiffeners (web 550X10mm, flange 250X20mm). Again, a larger stiffener spacing was found to be optimum for the total cost objective function compared to the weight objective function.

CLOSING REMARKS

Five stiffened plate configurations, widely used in shipbuilding, were studied to assess their structural integrity and to optimize them. It was found that four of those five panels did not meet the structural strength criteria established in this work. New designs of minimum total cost subject to stress, buckling, and standardization constraints were produced by discrete size optimization. Four of those five designs were further improved in shape optimization. Among all the structurally equivalent configurations of the five different stiffened plates, it was found thah i) The minimum weight design is stiffened plate 2 with 16 transverse stiffeners WT8X13, a transverse stiffener spacing bf 629.4mm (24.78 in), and plate thickness equal to 5mm (0.2 in). ii) The minimum work content design is stiffened plate 5 with 2 longitudinal stiffeners of web 870X12mm, flange 360X30mm, a longitudinal stiffener spacing 2375mm (93.50 in); and plate thickness equal to 30mm (1.18 in). iii) The minimum total cost design is stiffened plate 5 with 8 longitudinal stiffeners web 550X10mm, flange 250 X20mm; longitudinal stiffener spacing of 950mm (37.40 in); and plate thickness equal to 14mm (0.55 in). Other important qualitative conclusions are the following.

1. The weight of both cross stiffened plates (1 and 2) and unidirectionally stiffened plates (4 and 5) increases as the beam spacing increases. The rate of the weight increase, however, is different.

2. In general, the work content for stiffened plates decreases as the beam spacing increases. The rate of the work content reduction becomes smaller for larger spacing. In the case of stiffened plate 4, for beam spacings greater than a certain value, the work content increases.

3. The optimum beam spacing using total cost as the criterion was found to be 127 mm (5 in) to 559 mm (22 in) larger than the beam spacing for the weight optimum design.

Discrete optimization was performed in this study. The following question arises at this point. Will the discrete optimization performed in this work produce the optimal design sought, or is continuous optimization necessary? Continuous structural optimization, of course, would ignore standardization and call for customized plate and stiffeners. Some of the reasons why discrete optimization will provide applicable results are provided below.

Stiffener spacing is a naturally discrete variable. Assuming this variable to be continuous in a continuous optimization process, and then using the nearest discrete value would produce suboptimal results.

The number of discrete values of the other two variables used in this work are high enough to give an adequately dense matrix of designs. All integer plate thicknesses in millimeters greater than 5mm (0.2 in), 190 Bethlehem tees (16), and the 7 stiffeners in

reference (1) are considered. So, the optimal design that would be produced by continuous optimization is expected to be very close to that produced by the process developed in this paper.

Indeed, it is possible at the end of the discrete optimization process to measure how close the discrete optimum is to the continuous optimum without computing the latter. Monotonicity concepts in theoretical optimization, as well as common sense, point to the fact that the combined secondary and tertiary stress constraint must be active (19). That is, the maximum stress in psi in the structure must be 75.85 (11,000 psi). The actual stress value for the discrete optima in Tables VIII-XI are shown in the last column of each table. Obviously, reduction of plate thickness or stiffener cross-section would reduce the total structural weight, and produce a better design. Nonstandard plate thicknesses and stiffeners have to be used in such a case.

If standardization is mandatory - as is assumed to be the case in this paper- then discrete optimization is a better method to use. The alternative of applying continuous optimization and then selecting the nearest combination of plate-stiffener, cannot produce a superior design. On the contrary, if several discrete (standard) combinations are possible alternatives, the incorrect choice may k made.

ACKNOWLEDGEMENTS

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REFERENCES

1. Winkle, I and Baird, D, "Towards More Effective Structural Design Through Synthesis and Optimization of Relative Fabrication Costs," *Transactions of RINA, Nov. 1985.*
2. *Hatzidakis, N.* and Bemitsas, M.M., "Comparative Design of Orthogonally Stiffened Plates for Production and Structural Integrity, Part K Size Optimization," *Journal of Ship Production,* submitted in January 1993.
3. Hatzidakis, N. and Bemitsas, M.M., "Comparative Design of Orthogonally Stiffened Plates for Production and Structural Integrity, Part IL Shape Optimization," *Journal of Ship Production,* submitted in January 1993.
4. Moe, J. and Lund, S., "Cost and Weight Minimization of Structures with Special Emphasis on Longitudinal Strength Members of Tankers," *Transactions of RINA,* Vol. 110, 1968.
5. Boote, D., and Mascia, D., "On the Effective Breadth of Stiffened Platings," *Ocean Engineering,* Vol. 18, 1991, Pergamon Press.
6. Troisky, M.S., *Stiffened Plate - Bending Stability and Vibration,* Elsevier Scientific Publishing Co., Amsterdam, 1976.
7. Huffington, N.J., Jr., "Theoretical Determination of Rigidity Properties of Orthogonally Stiffened Plates," *Journal of Applied Mechanics, Transactwns of the ASME,* March 1956.
8. The MacNeal Schwendler Corporation, "MSC/NASTRAN Users Manual; Version 66; November 1988.
9. Schade, H.A., "The Effective Breadth of Stiffened Plating Under Bending Loads: *Transactions of SNAME,* November 1951.
10. Cho, K.N., "An Improved 2-Dimensional Grillage Method for Analyzing Orthogonally Stiffened Plated Grillage Structures," Ph.D. Thesis, Department of Naval Architecture and Marine Engineering, the University of Michigan, 1984.
11. Hughes, O.F., *Ship Structural Design, SNAME, 1988.*
12. Lincoln Electric Company, "The Procedure Hrmdbmk of Arc Welding: Cleveland, Ohio.
13. NASSCO, "Work Management Manual for Panel Assembly: UMTRI Report No. 71153.
14. Peterson Builders, Inc., "Work Management Manual in Shop Blast and Paint: UMTRI Report No. 70797.
15. Bernhard, B. for H. Bunch, "Micro Analysis of TAG(x) Production Costs: Report, The University of Michigan, Ann Arbor, April 1990.
16. Bethlehem Structural Shapes, Catalog 3277.
17. Kriezis, G.A., "Standardization in Ship Structural Design," *Journal of Ship Production,* Vol. *7,* February 1991.
18. Benford, H., "Fundamentals of Ship Design Economics," Report No. 86, Department of Naval Architecture and Marine Engineering, the University of Michigan, Arm Arbor, Michigan, April 1970.
19. Bemitsas, M.M., Human, M., Papakunbros, P., and Wilde, D.J., "Monotonicity Analysis of Constrained Optimization Problems: in New *Directions in Optimum Structural Design,* edited by R.H. Gallagher, O.C. Zienkiewicz, K.M., Ragsdell, and E. Atrek, Wiley Publishing Co., 1983, Chapter 13, pp. 285-308.

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Computer Aided Manufacturing in SmalI Shipyards: AU. S. and U. K Comparative Study

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ABSTRACT

Shipbuilders throughout the world are continuing to move toward Computer Integrated Manufacturing (CIM) Systems as a means of improving productivity, quality and competitiveness. The implementation of such systems provides unique challenges to all shipbuilders. One of the critical issues involves the choice of new versus existing computer systems (hardware and software) , the pace of change and the timing of implementation of new parts or totally new systems. These challenges and potential solutions are not only different for each shipyard, but are also significantly different for large and small shipyards.

Surveys of current uses and needs of small shipyards in the United States and the United Kingdom were conducted. These surveys were used to evaluate current systems and to make recommendations for potentially successful approaches to future implementation. The review focused on three major areas, including design (design, drafting, engineering, and lofting), production management (planning, estimating, material control, scheduling, purchasing, production/cost control, and quality control), and administration (payroll, time charging, and billing). Based on this review, recommendations concerning systems for implementation and a framework for integration is presented.

INTRODUCTION

In order to review the status of computer applications in small shipyards in the U.S. and the U.K., independent surveys of current uses and needs were conducted. The European Economic Community (EEC) definition for a small company is one with less than 500 employees. In this study, both for the U.S. and the U.K., the shipyards studied generally employ less than 200 people. The goal of the surveys was to i-denti.fy common needs and solutions, so that recommendations as to future directions in computer applications can be made. A cross section of small shipyards in the two countries were surveyed, either by mail, telephone or in person. Although the survey instruments and technique varied between shipyards and countries, in general, the following areas of potential computer application were considered:

DESIGN

- design
- drafting
- engineering
- lofting

PRODUCTION MANAGEMENT

- planning support
- estimating
- material control
- scheduling
- purchasing
- production/cost control
- quality control

ADMINISTRATION

- payroll
- time charging
- billing

The results of these surveys were then used to develop recommendations.

SURVEY RESULTS

In depth surveys were conducted in 8 U.S. and 12 U.K. shipyards, including shipyards involved in either reDair or new construction. Some did both but on separate sites. Due to this small sample size, the study sought levels of technology and trends which were representative of current practice in this segment of the industry. Thus no statistical analysis was conducted. Comparisons were also made to confidential surveys of Dutch, French and German yards carried out by several members of the U.K. team. These comparisons indicated that close similarities exist in those yards as well.

The results of the two surveys exhibited remarkable similarity between the two countries. [1,2] The primary differences noted were the specific software packages being employed, although there was significant overlap here as well.

In general, smaller shipyards have made only small capital investments in computer hardware and software. The primary investments are in computer aided design (CAD) systems and in simple software for word processing and accounting tasks. Nearly all hardware is stand alone PC'S. In most yards, little or no integration of computer generated information exists. A major cause of this situation is the relatively small number of trained computer users in the shipyards. In general, people are self–trained, and only employ computers to assist with their specific tasks. The major exception here is also in the area of CAD.

A large number of potential needs were identified. These include planning, estimating, production control and material control. These and other needs were mentioned in many individual surveys, but no consistent order or overwhelming priority was found.

Design

Most small shipyards involved in new construction have some design capability. This may be as little as a single person, but in all cases, it also includes CAD capability. Repair yards, on the other hand, had no in house CAD capability, and used external consultants when needed. The CAD systems are generally PC based. A wide variety of CAD software is employed, but if there is a "standard" , it is AutoCAD in the U.S., with SFOLDS, MAST and

AutoSHIP also common in the U.K. The majority of the use of CAD is for the generation of drawings, with first priority to the total vessel design, rather than separation by modules or problem areas. Information exchange with other departments and sub-contractors is normally by drawings. Despite CAD capability, most small shipyards do not develop a full set of detail design drawings, as is common in large shipyard practice. Instead, details are “left to the yard”, or not specified by design but established by and during production. Naturally, little consideration of design for production is given. What is considered are the major physical constraints of the ~yard, such as maximum lift capacity, rather than the development and refinement of a production strategy. Where employed, detail design drawings may be developed within the yard, either using CAD or manually, or by naval architectural sub–contractors.

Engineering computations are sometimes done using CAD related software at the shipyard design office. However, it is not uncommon for this work to be done manually or using software that is not directly integrated with the CAD software. Often, outside naval architectural consultants are employed to perform this work.

Lofting practice in small yards varies widely, both between the small yards and as compared to large yard practice. Direct development of Numerical Control (NC) data is uncommon. U.S. practice is moving quickly to the use of sub-contractors for the electronic development of NC data. U.K. practice does not yet seem to be following this pattern. The primary need is for good 3D hull definition, based on AutoCAD or other preliminary design software outputs. [3] There is also an apparent need for small yards to establish better internal control of the parts generation process. Thus, the use of sub-contractors may be reduced or some form of checking and tracking system will be needed. This can involve moving the sub-contractor to the shipyard for the NC data generation effort or moving a shipyard “lofter” to the sub–contractor. Additionally, the use of spreadsheets or other tracking tools may be required.

Production Management

Very little use (less than 10%) of production management software of any kind was found in the small shipyards in either the U.S. or U.K. Most systems are manual, with only informal inventory and production control systems found. There was no means of integrating any of these systems with each other or with design generated information. The most common computer application found here is some form of network scheduling software. Many such packages are available in both countries.

Another common feature of small yards in both countries is the lack of a repeatable product work breakdown structure (PWBS) or a build strategy. Instead, the small yards tend to use prior experience to plan construction. This results in most construction following traditional system by system

approaches, with steel work fabrication and assembly nearly completed before any outfit work begins. Without a PWBS, build strategy and interim products are not defined. Thus application of CIM technology for work station loading and work organization cannot be carried out effectively. The primary exception to this is the somewhat common practice of completing small superstructure units independent of the hull, and landing those directly on board. This is usually confined to bridge/wheel house units, which do have significant outfitting work completed prior to landing on board.

Administration

Many of the small yards do employ computers for typical administrative functions. These include payroll and invoicing/billing. These systems are exclusively stand alone systems, with no interface with any other computer applications in the shipyard.

SURVEY CONCLUSIONS

Small shipyards have and continue to employ computers as an increasing part of their operations. The primary uses to date have been in support of basic administrative functions and in design. Although overall investment in computer hardware and software has generally been low, the benefits derived from these investments have fallen far short of the potential. There are a number of reasons for this shortfall in computer productivity:

- use of the systems for single purpose activities;
- lack of an overall computer application strategy, including a plan for integration of applications;
- lack of a manufacturing system capable of deriving maximum benefit from computer applications, i.e. lack of a product work breakdown structure;
- shortage of trained (computer literate) personnel; and
- lack of capital for investment in computer hardware and software.

Key productivity benefits from the application of computer hardware and software can be obtained by better utilization of existing systems. The ability to develop direct NC steel cutting and perhaps pipe piece manufacturing instructions is still generally not available to the small shipyards. The rapid development of PC based 3D modeling software, and it's continual decrease in cost, will likely produce solutions to this problem in the near future. The obvious gap in computer application between the administrative functions and the design functions (the production management functions), however, significantly limits the productivity potential of computer applications in small shipyards. Additionally, the need for integration of information among functions in the shipyard is critical. Thus, the goal for small shipyards is to find low cost solutions to the key questions of effectively employing computers. This includes (1) integration of computer supported functions, (2) performing some or all of the

production management functions, and (3) incorporating a build strategy that relates the production management functions to marketing, preliminary design and estimating.

RECOMMENDED SMALL SHIPYARD COMPUTER STRATEGY

The availability of powerful CAD tools and the near term prospect of opportunities for direct NC control linked to these tools, makes this area a lower priority for small shipyard action in the near future. Naturally, these shipyards will need to evaluate the cost effectiveness of purchasing or expanding current systems to include these capabilities. The prospective market of the yard will dictate how effective CAD systems will be for these yards.

Since these decisions are somewhat more straight forward, the thrust of the recommendations will be toward the production management area, since this is the area that is currently addressed the least in most small shipyards. Effective computer (or manual) production management is dependent on two prerequisites:

- adoption of a product work breakdown structure, and
- system (data) integration.

Large vessel product work breakdown structures have been described in a number of sources. [4] Extension of this concept to small vessels has been considered, but still needs further definition. [5,6] The application of a PWBS is a prerequisite to successful computer application, because a PWBS employs the principles of group technology, which lead to repeatability. A key benefit of the use of computers is the reuse of data. A second key to effective computer utilization is the transfer of data used (or created) by one function to another function. This leads to the need for integration of computer data and company functions which employ the same data.

Spreadsheets

Spreadsheets are the computerized version of multiple column, multiple row financial accounting sheets. They are in common use and require little, if any training for users. They are very powerful software programs, however, and can be used to manage, update and transfer data, as well as providing simple arithmetic calculations. While they are not efficient for large data management tasks, their low cost and ease of operation make them an ideal choice for use by small shipyards. Many of the production management functions can be effectively performed using spreadsheets.

There are a number of very powerful spreadsheet programs that can be used on PC'S. Included among these are Lotus 123 and Excel, although there are many others available. Following are a series of examples of the potential uses of spreadsheets for production management functions.

Figure 1 presents a final ship account spreadsheet, summarizing the costs of tasks added and eliminated from a ship repair project. In a more complete spreadsheet application, this information

would be derived directly from a data base.

Figure 2 illustrates how a spreadsheet can be used to compile estimated cost information for labor, materials, sub–contract and tariff items. Appropriate percentages and rates are applied to these figures and a final total calculated. This form could be completed with actual cost information to provide a figure for the overall cost of a contract.

Figures 3 through 6 show several sections of a more detailed spreadsheet for cost analysis. Labor cost data from time cards is collated in terms of job number and work center on a weekly basis. This information can then be arranged and displayed to provide a wide range of status reports and planning and analysis tools. In Figure 3, a summary of costs for interim products is given on a weekly basis. Figure 4 summarizes the cost to date of steel work jobs undertaken. Information comparing each job to the volume of work by interim product and for the whole ship is also provided. Similar summaries are provided for other interim products, such as superstructure, engine room outfit, etc. In Figure 5, the costs of steel work labor are shown in a matrix of job number and week ending dates. Similar data can be provided for other trades. Figure 6 provides a summary of costs incurred in each work center.

Spreadsheets can also be used for data that is not directly related to costs. For example, Figure 7 shows a sequence of hull blocks that form a ship, indicating the work content by work category (cutting, bending, sub-assembly, etc.) . This data can be rearranged to show weekly work content by work category (Figure 8), and the same spreadsheet program can be used to plot the total shipyard work load by week (Figure 9). Although this example is for a large ship, the approach could be easily modified to be used in a small shipyard. This information can be used to help plan and schedule work to develop a smoother work flow.

Integration

Developing an integrated computer system is somewhat more difficult. At least two models are possible. The first involves the use of a central data base management system. Here again, many simple, effective software packages are available, including dBase, DataEase, FoxBASE, Paradox, and RBase. Using any of these systems, data is collected in categories associated with interim products identified by the PWBS. Figure 10 shows this simple model. Data contained in the main classes includes: ship details, estimate details, specification details, personnel records, time card information, material requirements and costs, labor requirements, purchasing information, schedules, work status, and accounting information.

For smaller applications, one or a few people may be involved in the computer applications. In this case, a formal data base integration system may not be necessary. In fact, integration may be achieved indirectly by the computer user, who would manually update critical

spreadsheet data as new information was generated. While not optimal, such a system would be inexpensive and provide a reasonable starting point.

CONCLUSIONS

Small shipyards face a difficult task in effectively employing computers. They generally face a shortage of capital for computer hardware and software investment, coupled with a shortage of trained and available personnel for performing computer work. In such a situation, inexpensive and off the shelf solutions are required. Spreadsheets and data base management systems offer these advantages. In order to effectively employ these programs, small shipyards must organize work to follow a product oriented work breakdown structure. Once such a system is in place, incrementally increasing use of computers will provide significant cost benefits.

Currently, small shipyards are not structured in a way to accept and utilize advanced software packages. They need to first move to a more structured shipbuilding system before attempting to employ and realize the benefits of CIM. Parts of a CIM system should be introduced incrementally, although a plan for the ultimate integration of these parts must be developed, updated and followed.

The real benefits of computer application are the supply of real time information to top management. This need was clearly understood by U.K. managers, particularly in repair yards, while their U.S. counterparts did not exhibit the same priority. Clear understanding of the benefits of computer application in small shipyards, including the need for integration was not evident. Such understanding, coupled with an investment in time and capital to plan and implement computer systems is required before significant advancement is likely.

REFERENCES

1. Braiden, P., Bruce, G., Hills, W., Kindleysides, S., and Snaith, G., "Computer Aided Engineering in Shipbuilding and Ship Repair, Final Report, " Engineering Design Centre, Newcastle University, October, 1992.

2. Storch, R., "Technology Survey of Small Shipyards in the Pacific Northwest, " Journal of ship Production, Vol. 9, No. 1, February, 1993.

3. Barry, C., Lane, K., Wilkerson, J., and Estes, C., "Application of Computer Lofting For Small Yards," SNAME PNW Section Meeting, Seattle, WA, 1991.

4. Storch, R. Hammon, C, and Bunch, H., Ship Production, Cornell Maritime Press, Centreville, Md, 1988.

5. Storch, R. and Leake, J., "Product Oriented Work Breakdown Structure For Small Commercial Vessels, " SNAME PNW Section Meeting, Bremerton, WA, June, 1992.

6. Leake, J., "The Producibility of Small Ships," Masters Thesis, University of Washington, Seattle, WA, March, 1993.

Contract Number: C111111			
Item No.	Description	Credit	Debit
	Original estimate	178000.00	
1	Cancel job number 530/31		150.00
2	Additional job number 450/12	275.00	
3	Additional job number 450/13	590.00	
4	Cancel job number 170/27		250.00
5	Cancel job number 126/32		850.00
6	Cancel job number 401/23		575.00
7	Additional job number 501/61	450.00	
8	Additional job number	950.00	
		180265.00	1825.00
	GRAND TOTAL	178440.00	

Figure 1: Ship account spreadsheet

Estimate Number:	E1111					
Specification	Description	Cost	Hours	Materials	Sub-Contractor's Cost	Total Cost
111/1	SERVICES					
c	Shore power (con/dis)	90				90
f	Cooling hose	80				80
	Water 16 days @ 30	480				480
i	Telephone (con/dis)	80				80
k	Sea trial		70		250	920
130/2	GENERAL SAFETY					
b	Fire hose	80				80
d	Halon gag				75	83
	Scaffold bridges		32			295
130/3	CLEANING					
	Accom Protection		40	450		864
					TOTAL	2770

Figure 2: Estimate compilation spreadsheet

Week Ending Date	Loft	Steel Cut	Weld	Pipe Bend	Engine Room Outfit	Superstructure	Labor	Week Total	Cumulative
11 Oct 91	264	0	0	0	0	0	0	264	264
18 Oct 91	256	0	0	0	0	0	0	256	520
25 Oct 91	305	0	0	0	0	0	0	305	825
01 Nov 91	609	304	0	0	0	0	0	913	1738
08 Nov 91	622	903	179	0	0	0	0	1704	3442
15 Nov 91	622	1777	483	0	0	0	0	2882	6324
22 Nov 91	658	2755	1430	574	0	0	772	6189	12513
29 Nov 91	698	3499	551	619	0	0	243	5609	18122
06 Dec 91	624	3656	2856	675	304	452	277	8843	26965
13 Dec 91	601	3557	4251	943	293	429	457	10532	37497
20 Dec 91	999	6119	6753	1476	1254	972	1207	18779	56276
27 Dec 91	0	0	0	0	0	0	0	0	56276
03 Jan 92	0	0	0	0	0	0	0	0	56276
10 Jan 92	625	3979	4186	929	304	1010	989	12022	68298
17 Jan 92	636	4000	4610	888	304	872	952	12260	80558
24 Jan 92	530	4001	4577	1044	304	850	971	12277	92835
31 Jan 92	320	2999	5041	1083	607	880	1243	12175	105010
07 Feb 92	322	3897	5144	1070	1245	511	1251	13440	118450
14 Feb 92	131	2265	5325	451	0	0	982	9155	127605
TOTAL	8821	43711	45385	9754	4614	5975	9344	128231	128231

Figure 3: Departmental labor cost summary

Job Code	Job Description	Cost to Date	% of Steel Work	% of Ship	Unit Cost	Measure Used	No. of Units
200	Hull unit prep. FRS 18.5-49.5	10213	7%	4%	165	tons	62
201	Focle unit prep. FRS 31-56.5	4023	3%	2%	297	tons	14
202	Hull unit fab. FRS 18.5-49.5	54667	38%	22%	882	tons	62
203	Hull construction to main deck	34142	24%	14%	255	tons	134
204	Superstructure construction	11531	8%	5%	684	tons	17
205	Outfit steel work/servicing etc.	4731	3%	2%	29	tons	165
206	Tank testing	2274	2%	1%	253	no. tanks	9
207	General work	3999	3%	2%	24	tons	165
208	Focle unit fab. FRS 31-56.5	4310	3%	2%	318	tons	14
209	Fabrication of fore end units	7623	5%	3%	406	tons	19
210	Bulwark fab. and construction	3817	3%	2%	947	tons	4
211	ER floors	0	0%	0%	0	tons	165
212	Holiday pay	3534	2%	1%	21	tons	165
	STEEL WORK CONTRACT TOTAL	144863	100%	59%	880	tons	165

Figure 4: Job cost summary report

Date	200	201	202	203	204	205	206	207	208	209	210	Week	Total
08 Nov 91	724.0	0.0	0.0	0.0	358.1	0.0	0.0	0.0	0.0	0.0	0.0	1082	1082
15 Nov 91	1115.2	0.0	840.7	0.0	303.6	0.0	0.0	0.0	0.0	0.0	0.0	2260	3342
22 Nov 91	2034.2	1543.4	0.0	0.0	607.2	0.0	0.0	0.0	0.0	0.0	0.0	4185	7527
29 Nov 91	1764.7	0.0	1734.6	0.0	303.6	0.0	0.0	0.0	0.0	0.0	0.0	3803	11330
06 Dec 91	1926.9	0.0	4281.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6209	17539
13 Dec 91	1292.3	0.0	5508.1	0.0	711.9	0.0	0.0	0.0	0.0	0.0	0.0	7512	25051
20 Dec 91	377.4	0.0	6840.4	942.8	804.4	0.0	0.0	0.0	0.0	0.0	0.0	12499	37550
10 Jan 92	612.1	0.0	4934.2	1717.5	303.6	0.0	0.0	0.0	0.0	0.0	445.0	8012	45562
17 Jan 92	0.0	712.5	5021.0	1148.8	488.0	0.0	0.0	0.0	607.2	0.0	445.0	8422	53984
24 Jan 92	0.0	712.5	3626.8	1666.6	1210.6	0.0	0.0	210.1	965.3	0.0	0.0	8392	62376
31 Jan 92	0.0	303.6	4037.6	1357.0	628.0	0.0	0.0	886.8	607.2	0.0	0.0	7820	70196
07 Feb 92	0.0	242.9	3841.0	3120.1	307.6	0.0	0.0	725.1	303.6	0.0	306.6	8847	79043
14 Feb 92	0.0	0.0	3930.4	2799.1	350.6	0.0	0.0	0.0	0.0	0.0	206.9	7287	86330
TOTAL	9846	3515	44597	12752	6377	0	0	1822	2483	0	1404	86330	86330

Figure 5: Steelwork job cost report (labor)

Date	Loft	Steel Cut and Weld	Pipe Bend	Engine Room Outfit	Superstructure Outfit	Labor	Week	Total
29 Sep 91	318.2	0.0	0.0	0.0	0.0	0.0	318	318
6 Oct 91	308.6	0.0	0.0	0.0	0.0	0.0	309	627
13 Oct 91	263.8	0.0	0.0	0.0	0.0	0.0	264	891
20 Oct 91	256.1	0.0	0.0	0.0	0.0	0.0	256	1147
27 Oct 91	305.3	0.0	0.0	0.0	0.0	0.0	305	1452
03 Nov 91	608.9	303.6	0.0	0.0	0.0	0.0	913	2365
10 Nov 91	622.0	1082.0	0.0	0.0	0.0	0.0	1704	4069
17 Nov 91	622.0	2259.6	0.0	0.0	0.0	0.0	2882	6950
24 Nov 91	658.2	4184.8	573.8	0.0	0.0	772.4	6189	13139
01 Dec 91	697.7	3802.9	866.0	0.0	0.0	242.8	5609	18749
08 Dec 91	623.7	6208.8	978.7	303.6	451.5	276.6	8843	27592
15 Dec 91	600.8	7512.3	1239.4	293.2	429.1	456.8	10532	38123
22 Dec 91	999.1	12498.6	1849.3	1253.8	972.1	1206.6	18779	56903
29 Dec 91	0.0	0.0	0.0	0.0	0.0	0.0	0	56903
05 Jan 92	0.0	0.0	0.0	0.0	0.0	0.0	0	56903
12 Jan 92	625.4	8012.4	1232.7	303.6	858.2	989.5	12022	68924
19 Jan 92	635.6	8422.5	1191.5	303.6	755.2	952.0	12260	81185
26 Jan 92	530.3	8391.8	1347.8	303.6	733.0	970.6	12277	93462
02 Feb 92	320.1	7820.2	1386.6	607.2	797.2	1243.5	12175	105636
09 Feb 92	321.8	8847.0	1374.0	1245.3	400.7	1251.0	13440	119076
16 Feb 92	130.6	7287.0	755.1	0.0	0.0	981.9	9155	128231
23 Feb 92	254.4	6414.8	1362.4	180.5	0.0	996.2	9208	137439
TOTAL	9702.8	93048.3	14157.3	4794.4	5396.9	10339.8	137439	162855

Figure 6: Activity cost summary

Sequence Number	Unit Number	Weight, Tons	Cutting Weeks	Cum Cutting Weeks	Bending Weeks	Cum Bending Weeks	Sub-Asbm Weeks	Sub-Asbm Weeks	Main Asmb Weeks	Main Asmb Weeks	Paint Weeks	Cum Paint Weeks	Erect Weeks	Cum Erect Weeks	Total Weeks
1	101	73.54	0.08	0.08	0.00	0.00	0.97	0.97	0.54	0.54	0.18	0.18	0.33	0.33	2.11
2	326	89.62	0.10	0.18	0.00	0.00	1.18	2.15	0.66	1.20	0.22	0.41	0.41	0.74	2.57
3	544	53.77	0.06	0.24	0.00	0.00	0.73	2.88	0.41	1.61	0.14	0.55	0.25	1.00	1.60
4	654	67.77	0.08	0.32	0.00	0.00	0.89	3.77	0.50	2.11	0.17	0.72	0.31	1.30	1.94
5	102	98.48	0.11	0.43	0.00	0.00	1.30	5.07	0.72	2.83	0.25	0.96	0.45	1.75	2.82
6	210	78.69	0.09	0.52	0.00	0.00	1.04	6.10	0.58	3.41	0.20	1.16	0.36	2.11	2.26
7	211	58.94	0.07	0.58	0.00	0.00	0.78	6.88	0.43	3.84	0.15	1.31	0.27	2.38	1.69
8	322	76.98	0.09	0.67	0.00	0.00	1.01	7.89	0.57	4.41	0.19	1.50	0.35	2.73	2.21
9	323	78.69	0.09	0.75	0.00	0.00	1.04	8.93	0.58	4.99	0.20	1.70	0.36	3.08	2.26
10	542	87.54	0.10	0.85	0.00	0.00	1.15	10.08	0.64	5.63	0.22	1.92	0.40	3.48	2.51
11	655	56.12	0.06	0.91	0.00	0.00	0.74	10.82	0.41	6.05	0.14	2.06	0.26	3.74	1.61
12	105	97.94	0.11	1.02	0.20	0.20	1.29	12.11	0.72	6.77	0.24	2.30	0.45	4.18	3.00
13	214	100.43	0.11	1.13	0.20	0.40	1.32	13.43	0.74	7.50	0.25	2.55	0.46	4.64	3.08
14	432	71.92	0.08	1.21	0.14	0.54	0.95	14.37	0.53	8.03	0.18	2.73	0.33	4.97	2.21
15	541	54.83	0.06	1.27	0.11	0.65	0.72	15.10	0.40	8.44	0.14	2.87	0.25	5.21	1.68
16	653	57.34	0.06	1.34	0.11	0.76	0.75	15.85	0.42	8.86	0.14	3.01	0.26	5.48	1.76
17	104	57.90	0.06	1.40	0.00	0.76	0.76	16.61	0.43	9.23	0.14	3.16	0.26	5.74	1.66
18	106	76.98	0.09	1.49	0.00	0.76	1.01	17.62	0.57	9.85	0.19	3.35	0.35	6.09	2.21
19	212	69.51	0.08	1.57	0.00	0.76	0.91	18.54	0.51	10.36	0.17	3.52	0.32	6.40	1.99
20	324	58.94	0.07	1.63	0.00	0.76	0.78	19.31	0.43	10.79	0.15	3.67	0.27	6.67	1.69
21	325	76.54	0.09	1.72	0.00	0.76	1.01	20.32	0.56	11.36	0.19	3.86	0.35	7.02	2.19
22	434	84.70	0.09	1.81	-0.00	0.76	1.11	21.44	0.62	11.98	0.21	4.07	0.39	7.41	2.43
23	436	68.55	0.08	1.89	0.00	0.76	0.90	22.34	0.50	12.48	0.17	4.24	0.31	7.72	1.97
24	652	92.90	0.10	1.99	0.00	0.76	1.22	23.56	0.68	13.17	0.23	4.48	0.42	8.14	2.66
25	103	102.98	0.11	2.10	0.00	0.76	1.36	24.92	0.76	13.92	0.26	4.73	0.47	8.61	2.95
26	213	103.43	0.11	2.22	0.00	0.76	1.36	26.28	0.76	14.68	0.26	4.99	0.47	9.08	2.97
27	216	97.94	0.11	2.33	0.00	0.76	1.29	27.57	0.72	15.40	0.24	5.24	0.45	9.52	2.81
28	431	49.52	0.06	2.38	0.00	0.76	0.65	28.22	0.36	15.77	0.12	5.36	0.23	9.75	1.42
29	433	92.90	0.10	2.49	0.00	0.76	1.22	29.44	0.68	16.45	0.23	5.59	0.42	10.17	2.66
30	435	59.83	0.07	2.55	0.00	0.76	0.79	30.23	0.44	16.89	0.15	5.74	0.27	10.44	1.72
31	546	69.75	0.08	2.63	0.00	0.76	0.92	31.14	0.51	17.40	0.17	5.92	0.32	10.76	2.00
32	547	65.97	0.07	2.70	0.00	0.76	0.87	32.01	0.49	17.89	0.16	6.08	0.30	11.06	1.89
33	651	84.01	0.09	2.80	0.00	0.76	1.11	33.12	0.62	18.51	0.21	6.29	0.38	11.44	2.41
34	215	57.90	0.06	2.86	0.12	0.88	0.76	33.88	0.43	18.93	0.14	6.44	0.26	11.70	1.78
35	321	123.87	0.14	3.00	0.00	0.88	1.63	35.51	0.91	19.84	0.31	6.75	0.56	12.27	3.55
36	327	56.87	0.06	3.06	0.00	0.88	0.75	36.26	0.42	20.26	0.14	6.89	0.26	12.53	1.63
37	543	88.92	0.10	3.16	0.00	0.88	1.17	37.43	0.65	20.92	0.22	7.11	0.40	12.93	2.55
38	545	60.73	0.07	3.23	0.00	0.88	0.80	38.23	0.45	21.36	0.15	7.26	0.28	13.21	1.74
39	656	91.05	0.10	3.33	0.18	1.06	1.20	39.42	0.67	22.03	0.23	7.49	0.41	13.62	2.79
		2996.29	3.33		1.06		39.42		22.03		7.49		13.62		26.96

Figure 7: Example spreadsheet for work content by block

Workarea	Week 0	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13
Cutting		899.82	899.82	899.82	296.94									
Bending						299.63	299.63	299.63	299.63	299.63	299.63	299.63	299.63	299.63
Subasmbl		69.93	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01
Mainasmbl														
Painting														
Erection														
Total	0.00	969.75	975.83	975.83	372.95	375.64	375.64	375.64	375.64	375.64	375.64	375.64	375.64	375.64

Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23	Week 24	Week 25	Week 26	Week 27	Week 28	Week 29
299.63															
76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01
				116.97	136.01	136.01	136.01	136.01	136.01	136.01	136.01	136.01	136.01	136.01	136.01
													214.02	214.02	214.02
													178.19	219.99	219.99
375.64	76.01	76.01	76.01	192.98	212.02	212.02	212.02	212.02	212.02	212.02	212.02	212.02	604.23	646.03	646.03

Week 30	Week 31	Week 32	Week 33	Week 34	Week 35	Week 36	Week 37	Week 38	Week 39	Week 40	Week 41	
											0.00	2996.40
											0.00	2996.29
76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	76.01	38.00	0.00	2996.29
136.01	136.01	136.01	136.01	136.01	136.01	136.01	136.01	136.01	136.01	23.12	0.00	2996.29
214.02	214.02	214.02	214.02	214.02	214.02	214.02	214.02	214.02	214.02	214.02	0.00	2996.29
219.99	219.99	219.99	219.99	219.99	219.99	219.99	219.99	219.99	219.99	178.19	0.00	2996.29
646.03	646.03	646.03	646.03	646.03	646.03	646.03	646.03	646.03	646.03	453.34	0.00	

Figure 8: Example spreadsheet showing weekly workloads

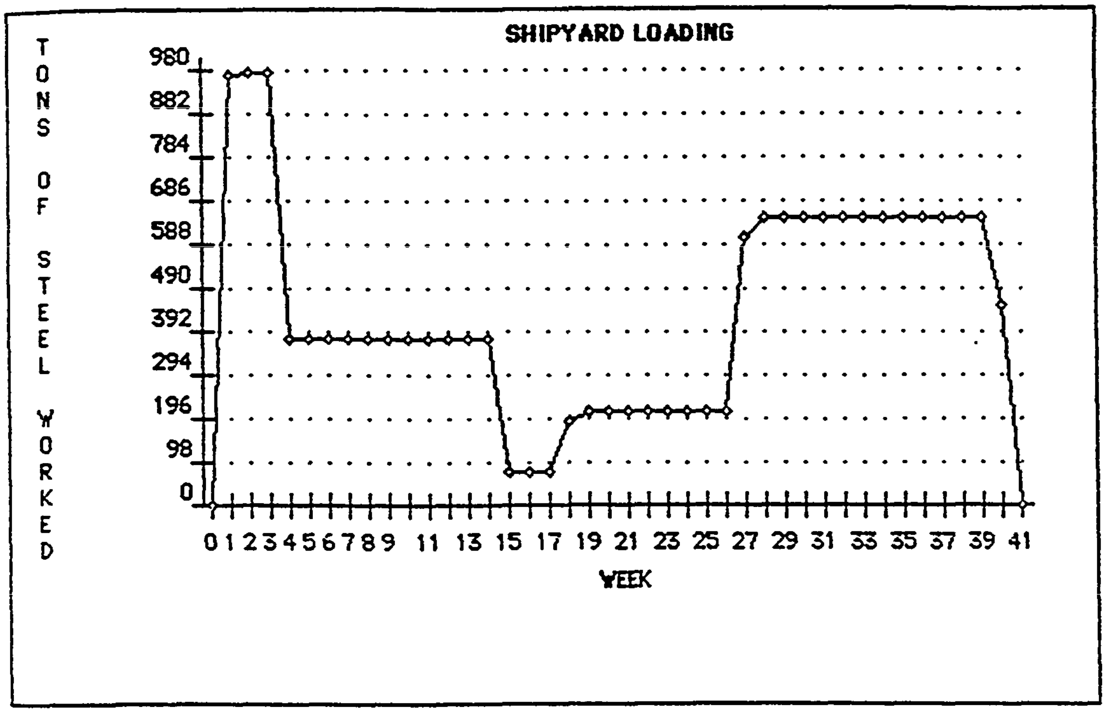

Figure 9: Shipyard Loading Histogram

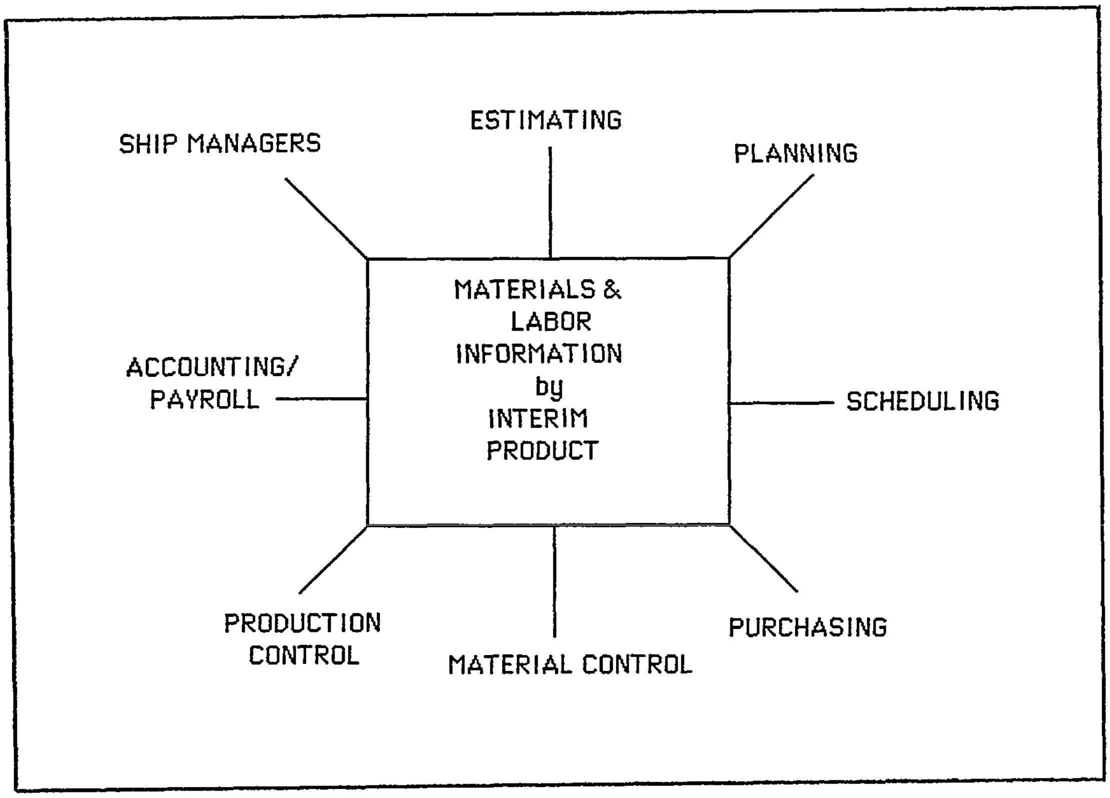

Figure 10: Integration Model Based on Interim Products

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A Conceptual Design Study of the Construction of Hydrodynamic Control Surfaces

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ABSTRACT

Hydrodynamic control surfaces are traditionally built as steel fabrications. While this gives a very smmg structure, it is rather heavy and costly, it is clifilcult to achieve smooth surfaces, and the steel is susceptible to erosion, corrosion and marine fouling. This paper describes a conceptual design study aimed at creating a competitive advantage for the manufacturers of control surfaces by using modem materials in a composite structure. The conceptual design process, as applied here, starts by specifying the design requirements for the construction of control surfaces, and listing a set of criteria against which the concept designs can be evaluated. A total of six concept designs are described and evaluated in comparison with a traditional steel fabrication, and one concept is selected for further development. This comprises a light steel frame structure, with thin steel inner face plates enclosing an inner core that is filled with polyurethane foam. The sudhce shape is also formed with Polyurethane foam poured between the faceplates and a surface mold plate. Finally, the surface is sprayed with a polyurethane elastomer coating.

NOMENCLATURE

A = area of control surface
B = balance
c = mean chord
Cp = pressure coefficient
Cr = root chord
C1 = tip chord
Ef = elastic modulus of foam
E s = elastic modulus of solid polymer
g = acceleration due to gravity
h = head of water
M = mass
p = local pressure
pd = dynamic pressure
p_a = atmospheric pressure
S = span
Tr = root thickness
Tt = tip thickness
u = local velocity
u = free stream velocity
E = sweep or rake angle
p = water density
pf = density of foam
ps = density of solid @ymer
φ = volume fraction of foam

CONVERSION OF UNITS

1 meter= 3.281 feet
1 millimeter= 0.04 inch
1 kilogram= **2.2** pound
1 Newton= 0.225 pound force
1 kilonewton = 0.1004 tons force
1 kilonewton meter =738 pound force foot
1 kilogramlcu. meter = 0.0624 lb/cu. ft
1 Megapascal = 145 psi
*1= $1.57

INTRODUCTION

Hydrodynamic control surfaces are used on ships and submarines to conned ship motions, and rue found in the form of rudders, stabilizer fins and hydroplanes. They are traditionally built as steel fabrications, with WOOL reinforced plastics, and cast nylon used as alternatives for small size control surfaces. Some recent designs of hydroplanes and rudders for submarines

have utilized syntactic foams and non-metallic composites (l).

Steel fabrication of hydrodynamic control surfaces is well-suited to the manufacturing facilities of marine engineering companies and shipyards, and provides a control surface that can be easily repaired throughout the world using the skills and facilities of any well equipWd ship repair yard. However, there are also a number of disadvantages with a steel fabrication. It is necessary to use relatively thick steel plate with internal stiffeners to achieve an accurate and smooth surface profile. This leads to a heavy construction that requires stitch welding and a fair amount of dressing of welds, all of which leads to high cost. The steel surface is also affected by corrosion, marine growth, and cavitation erosion. It therefore requires good anti-fouling, with periodic maintenance to retain the surface in good condition.

The objective is to improve the competitive position of marine engineering companies in developed nations through the use of modem technologies. The goals are to reduce the cost and weight of hydrodynamic control surfaces, while also impmving the geometrical accuracy and smoothness of the surfaces, and their resistance. to corrosion, erosion, and marine fouling. This has been achieved by developing a methodology for the design and manufacture of hydrodynamic control surfaces utilizing modem material and construction technologies, using a design approach to look at how best to utilize existing modem materials in a traditional product

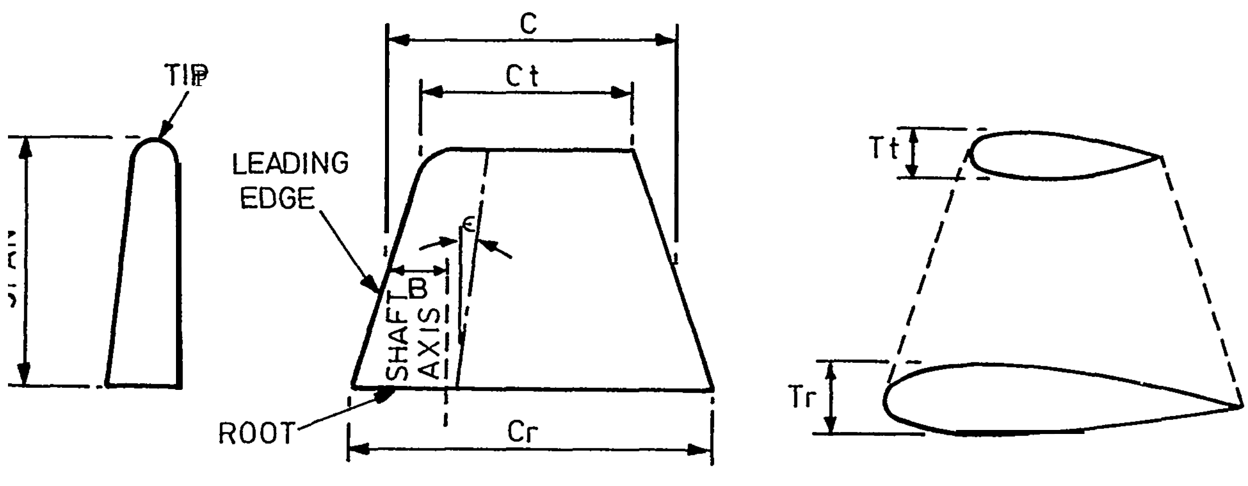
This paper reports on the conceptual design phase of the work during which many alternative design solutions were devised and evaluated, a preferred solution adopted, and then developed to the point where the detailed design of a prototype stabilizer fin could be undertaken. The bases for this work were the design requirements for hydrodynamic control surfaces, and the criteria against which the alternative concept designs could be evaluated.

DESIGN REQUIREMENTS

The design requirements for the construction of hydrodynamic control surfaces cover rudders and roll stabilizer fins for ships, and hydroplanes and rudders for submarine applications. These latter items require special consideration because of the high hydrostatic pressure loadings. The requirements have been formulated as a result of correspondence and meetings with leading UK shipyards and marine equipment manufacture about the use and fabrication of current designs, and by analysis of the loadings.

Types and Sizes of Control Surfaces.

This study is restricted to cantilevered control surfaces carried on a socketed shaft, such as ase used



= Span
t = Tip Chord
r = Root Chord
lean Chord, C = 0.5*(Ct + Cr)
alance = B/C

Tt = Tip Thickness
Tr = Root Thickness
ϵ = Rake or Sweep Angle
Aspect Ratio, a = S/C
Thickness Ratio = T/C

Figure 1. Parameters for a Trapezoidal Control Surface

for spade rudders and stabilizer fins. Other forms of hydrodynamic control surfaces, such as Mariner rudders, have less highly stressed interfaces with the ship, and it is therefore anticipated that methods of construction developed for cantilevered surfaces will be easily adapted to surfaces that are more uniformly supported. A trapezoidal plan form shape is used with the geomehy of the control surface defined by the parameters given in Figure 1.

The range of sizes of control surfaces depends on the application. For commercial and naval applications (i.e. not including yachts), the following ranges represent current practice.

Trapezoidal stabilizerjins:
1.0 m^2 to 15 m^2 (10 ft^2 to 160 ft?)

Rectangular flapped fins:
2.5 m to 20 m (25 ft^2 to 215 ft^2)

Submarine rudders & hydroplanes:
10 m to 30 m (105 0f? to 320 ft^2)

Spade rudders:
up to about 25 m^2 (270 ft^2)

Larger ruddem are usually supported on a horn.

The majority of hydrodynamic control surfaces are trapezoidal in plan form, with a raked leading edge. The shaft is fitted on an axis passing close to the center of pressure loading on the surface, so as to balance moments due to the loads. On trapezoidal surfaces a balance position behveen 20% and 30% of the chord is used, while for a flapped surface a balance of 30% to 35% is required. Aspect ratios may vary from about 0.5 to 2.5. The hydrodynamic section most commonly employed is the symmetrical NACA (National Advisory Committee on Aeronautics) 4 digit section with thickness between 12% and 33%. The thickness is determined primarily by the need to accommodate the shaft. There is slightly higher drag with thicker sections, but with the advantage of a flatter pressure distribution, giving less face cavitation. The tip shape can be faired or square.

Loadings

The following sources of loading need to be considered when undertaking the structural design of a hydrodynamic control surface.

1. Hydrodynamic loads due to the flow of water over the surface which vary with the speed and frequency of rotation of the surface about its shaft.
2. Hydrostatic loads due to the pressure head of water above the control surface.
3. Impact loads due to collision with debris in the water, or with quay struchues. The surfaces should also resist damage due to loose items Ming dropped onto them during manufacture, or in dry dock

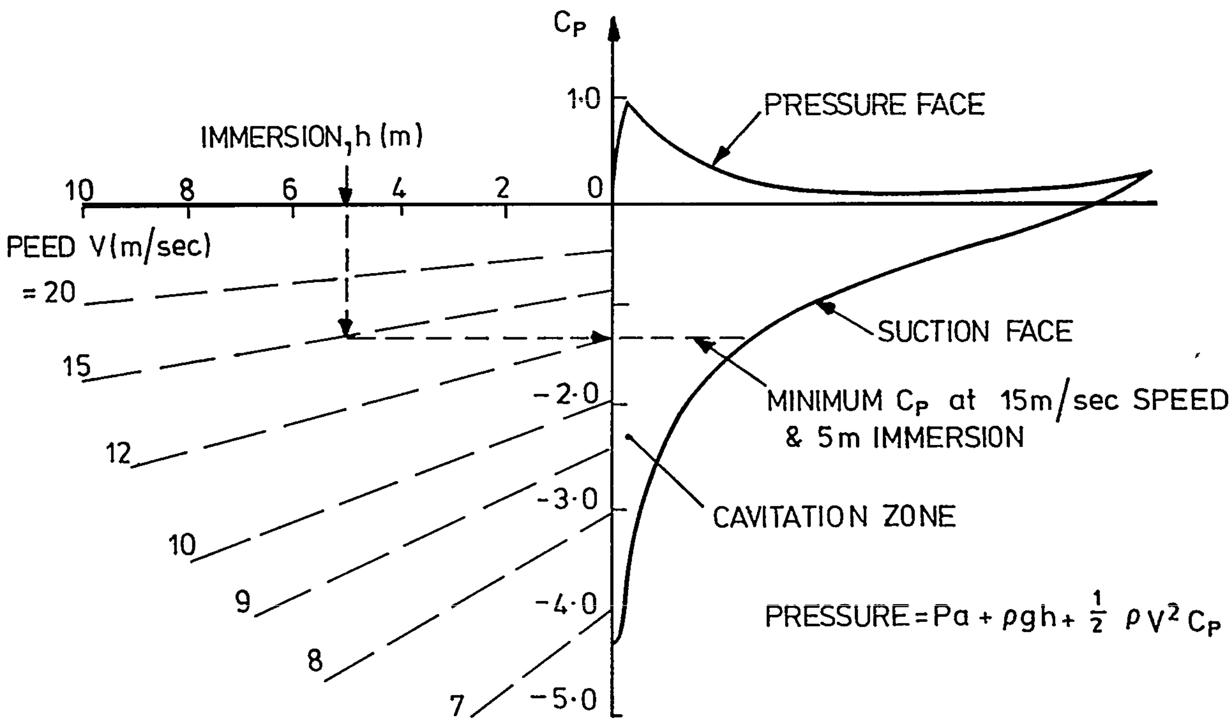


Figure 2. Pressure Coefficients on a Control Surface at Cl=1

4. Handling loads during manufacture.

5. Shock Loads. Control surfaces built for military applications me required to withstand a specified level of shock horn underwater explosions.

Hydrodynamic Loading. Hydrodynamic loading ruises from the pressure distribution that occurs on the control surface as a result of the variation in the velocity of flow over the surface. Figure 2 shows a typical pressme distribution for a control surface with an aspect ratio of 1.0, and an angle of incidence of 25 degrees where the pressure coefficient is given by:

$$c_p = \frac{p - p_o}{\frac{1}{2}\rho U^2} \qquad (1)$$

This figure is used for design purposes, and is based on data for NACA four digit sections given by Abbott & Doenhoff (2). The minimum value of C_p that can be sustained without cavitation depends on the immersion of the lifting surface, and is given for a range of speeds from 7 m/s up to 20 m/s (13.6 - 38.9 knots). The minimum value of C_p is applied over that part of the surface where potential values less than the minimum are indicated.

The criteria stated so far indicate worst loading conditions that m treated as static loads for design P~ses, since they will usually only occur under casualty conditions (i.e. when a fault causes maximum angle of incidence at maximum ship speed). Fatigue loads will be lower than the maximum static loads, since it is normal practice to limit angles so as to prevent C_p from reaching the cavitation limit under normal working conditions. Design of the structure of a hydrodynamic control L.. face for a specific application should, of course, be checked against the loads that will be experienced in that application.

Hydrodynamic Loading Limits. The pressure loading that a particular hydrodynamic control surface can cmy is limited by the ability of the cantilever shaft to carry the bending moment induced by the pressure loading, and the control surface must be operated so as not to exceed this loading. By assuming an allowable fatigue stress of 150 MPa (22,000 psi), which is typical current design practice, approximate maximum working loads are derived and shown in Figure 3 for a control surface with any combination of area, aspect ratio, and section thickness ratio. The casualty load is taken as approcximately twice the working load, although it maybe higher in high speed ships.

Torsional Loads. The torsional load on a hydro- dynamic control surface is given by the first moment of the pressure loading measured about the shaft axis. The maximum pressure load on a control surface is only slightly influenced by the rate at which the angle of incidence is changing (called the slew rate), but the center of pressure is considerably influenced by the slew rate, which must therefore be taken into account in the torsional load calculation. A slew rate which acts to increase the angle of incidence causes a small increase in the pressure loading, and a movement of the center of pressure toward the trailing edge of the control surface. Due to a paucity of data on this effect, empirical estimates of torsional load are commonly used, with the relevant parameters being rues, chord and slew rate of the control surface, and ship speed. The balance is chosen to minimize torsional load. With the load as derived from Figure 3 the maximum working torque is given approximately by

$$Z = FC(0.03+0.01 \ C:) \qquad (2)$$

where t = torque in kN.m (lbs.ft)
F= load in kN (lbs)
c = chord in m (ft)
s = slew rate in degrees per second
v = ship speed in m/s (ft/see)

For casualty conditions the load should be doubled and the factor 0.03 increased to 0.045.

Impact Loading. The requirement to resist impact load in service is specified in terms of a collision at design speed with a tree trunk 120 mm

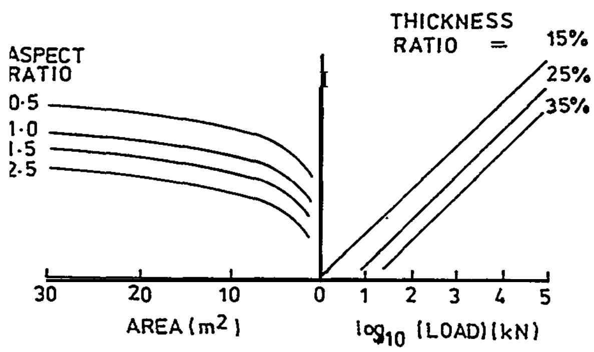


Figure 3. Hydrodynamic Load Limits

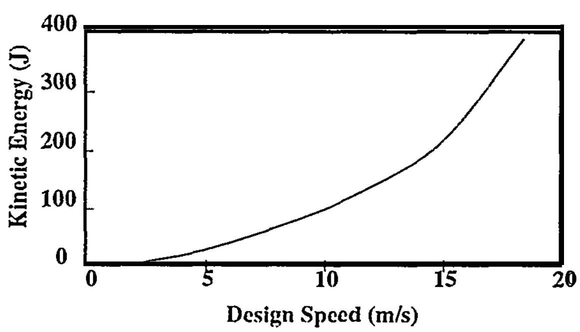


Figure 4. Design Values for Impact Loading

(4.7 in) in diameter and 2 m (6.6 ft) long. The effects of the impact load depend on the contact area between the object and the surface, and on the overall stiffness of the control surface. Estimated values of the impact loads at different design speeds are shown in Figure 4.

For submarines, serious collisions can occur with quays when docking. This is because the surfaces extend beyond the beam of the submarine, so the probability of impact damage increases for submruine fins, hydroplanes and rudders. Special attention to impact loads should therefore be included in the evaluation of submarine control surfaces.

Requirements for loadings due to grounding are not specified, and will not be considered in the design criteria.

Fatigue. The design life for stabilizer fins is 20 years, which is assumed to correspond to 10^7 cycles at maximum working load with a frequency of 0.1 Hz. For submarines the plamed life is 25 to 30 years, but a duty of 10^7 cycles is also specified due to a lower utilization rate. Rudders are only occasionally used at maximum loading.

Factors of Safety. For metals, the factor used for service load is 3.125 on yield strength, or 5.0 on ultimate strength, while for casualty loads, a factor of 1.5 on yield strength is used. For fiber reinforced plastic, factors from 4.0 for static loads to 6.0 for fatigue loads are used as recommended by Chalmers (3).

General Construction Requirements

Surface Coatings. These should be at least as resistant as the painted steel surface that is currently used. The coating should remain in gcmd condition after 3 years in service, and should provide Sufficient protection to ensure that the surface structure will still be repairable after 6 years without any intermediate maintenance. Surface coatings should be resistant to cavitation erosion and marine fouling.

Accuracy of Profiie. Geometric tolemncw should be such that all parts of the lifting surface will be within t 0.003 K(A= fm area) of the drawing size.

Surface Smoothness. Surface smoothness can be measured by holding a flexible batten (appmx. 500 mm (20 in) long) against the surface and checking that a designated feeler gauge cannot be inserted between batten and the surface: for the forward 25% of the surface, the gauge should be 2.5 mm (0.1 in) thick, for the remainder of the surface, the gauge should be 5.0 mm (0.2 in) thick. Additionally, the rate of deviation of the surface of the plate from a smooth curve should not exceed a slope of 1:10 on the forward 25% of the surface and 1:5 on remainder of the surface.

Shaft Requirement. A removable shaft is not an absolute requirement even though they are fitted to many control surfaces for ease of repair. While there is no design constraint on the shaft interface, the shaft must be perpendicular to the root plate and fitted at a balance of between 20% and 35%. The shaft must be circular at the hull line.

CONCEPTUAL DESIGN APPROACH

The approach adopted for the conceptual design process involves the following steps.

1. Derive a set of criteria from the design requirements for use in evaluating the relative merits of the various concept design proposals. It is important that the criteria should be set prior to devising the concept designs, so as to avoid subconsciously writing the criteria in terms advantageous to a favored concept.
2. Devise a set of values for the design parameters to define a standard control surface based on a typkal application for use in comparative evaluation of the concept proposals. The application chosen for this study is fin stabilization of ship roll.
3. Divide the problem into a number of sub-problems based on functional elements of the structure of the control surface.
4. Devise anumberof solutions to each sub-problem, and evaluate their feasibility and cost.
5. Use various combinations of the sub-problem solutions to create a number of concept design proposals. Test for feasibility and discard any that are not viable.
6. Generate data for each concept design proposal for the standard control surface defined instep 2.
7. Evaluate the alternative concept design proposals against the criteria defined instep 1.
8. Select the best design solution,
9. Develop the selected design.

Evaluation Criteria

The evaluation criteria can be grouped into three categories relating to technical, manufacturing and commercial factors. Criteria within each of these categories are listed below with a discussion of desirable characteristics.

Technical Criteria

Mass of the surface. A specific objective of the project is to reduce the mass of control surfaces by a target of 25% relative to current fabrication

methods. The mass of each concept is calculated and indicated in the evaluation chart The mass of a steel fabricated trapezoidal fin is given approximately ax

$$M = 350 A I^{\text{“fi}} \text{ kg} \quad (=40 \; Al^{\text{”x}} \text{ lbs}) \qquad (3)$$

where A is control surface area in meters² (feet?).

Accuracy of Surface. Concept designs are ranked according to the ease of achieving the design requirement for accuracy.

Appearance of Surface. Users expect control surfaces to be smooti and this can also be important for the hydrcxiynamic performance, although the NACA 4-digit sections are quite tolerant to surface roughness.

Resistance to Erosion (Cavitation). Some degree of cavitation will nearly always occur on a control surface (unless deeply submerged), even if only within the tip vortex. Painted mild steel is not good at resisting erosion and some improvement is desirable.

Resistance to Marine Foaling. Skin materials must either resist marine fouling, or be compatible with marine anti-fouling paints. The latter is desirable in any event since all surfaces are liable to be painted, whether or not intended.

Resistance of Skin to Impact. The skin should not be breached by impact with underwater, or floating objects, particukly if the substrate material may be damaged by exposure to sea water.

Resistance of MateriaIs to Sea Water. Materials should not deteriorate on contact with sea water, nor should they absorb more than a minimal amount of water.

General Resistance to Impact. Control surfaces should have the greatest possible resistance to impact loads without damage to the main shaft bearings and actuation equipment and withoutbreaching the water-tight integrity of the ship. The sequence of damage under increasing impact loads should be

1. impact energy absorbed without damage
2. darnage to skin and immediate substrate without urgent need for repair
3. collapse of control surface structure
4. bending of shaft
5. damage to bearings
6. failure of seals, or structural damage, leading to flooding of the ship.

Resistance to Hydrostatic Loads. An estimate is given of the maximum depth in meters at which the control surface can safely operate.

Other Technical Criteria. The concept designs are each ranked according to resistance to static loads; resistance to fatigue loa& resistance to shock load,y lif~ shaft joint integrity; overall design integrity.

Manufacturing Criteria

It is necessary to evaluate the technical risk involved in the use of the materials proposed for each concept design, and also the extent to which the use of the materials will either require new methods to be introduced by the manufacturer, or involve subcontracting of all or part of the process.

Materials. The concept designs are ranked according to their current use in marine engineering, their use in similar applications and on a similar scale, or if they represent a new development.

Manufacturing Method. The concept designs are ranked in order of preference for:

1. methods currently used in marine engineering
2. methods that could be introduced with low training and facilities cost
3. methods that could be introduced with an investment in new staff, training and facilities
4. work that would need to be subcontracted.

Commercial Criteria

Estimates are made for each cmcept design ofi the total manufacturing cost and the cost of the control surface alone, the objective being to reduce the cost of the control surface by 40% relative to the steel fabrication; the direct material COSL excluding the shaft the cost of all subcontract activity, including any transport or other costs associated with the subcontract; and the direct manufacturing hours, excluding those for the finshaft. These are included in the total costs at a rate of £35 ($55) per hour for machining activities and 225 ($40) per hour for fabrication activities.

STANDARD FIN PARAMETERS

As part of the overall project a prototype stabilizer fin has been built with the same geometry as an existing design fitted to a British fisheries protection vessel. This is a trapezoidal fin area of 1.5 m² (16 ft²) area, with the folIowing geometric characteristics:

Fin SIXtiOll,X	NACAO015
Aspect ratio:	
Taper ratio:	0.488
Fin shaft balance:	26.5%
Zero rake chord:	32.2%

Fin Area (m^2)	1.5	5	*10*	*15*	(X *10.76fi?)*
Span (mm)	1225	2250	3160	3870	(*x* 0.04 in)
Mean Chord (mm)	1225	2250	3160	3870	(x 0.04 in)
Root chord (mm)	1646	3024	4247	5201	(x 0.04 in)
Maximum fin angle (deg)	25	25	25	25	
Shaft Diameter (mm)	170	260	390	620	(x 0.04 in)
Normal Load &(kN)	66	220	480	1300	(X 225 lbf)
Hydrodynamic torque (kNm)	7.5	57	190	820	(X 720 Ibf.ft)
Casualty load &(kN)	186	620	1350	3660	(X 220 lbf)

Table I. Fin Parameters

Leading edge rake 12.5°
Trailing edge rake 25°

The conceptual design evaluation is carried out primarily on the 1.5 m^2 (16 ft^2) fin, with results also being extrapolated to a range of fin sizes up to 25 m^2 (270 ft^2). The parameters for the full range of fin sizes considered are given in Table I.

FUNCTION ANALYSIS

For the purposes of the conceptual design the overall problem is divided into four sub-problems by examining the primary functional requirements of a control surface. These require the provision of: a rigid hydrofoil surface, a stucture to carry the hydrodynamic forces horn the surface to a shaft interface, a shaft to transmit the forces back into the ship's hull structure, and an interface between the control surface and the shaft. A number of solutions to each sub-problem arc devised and evaluated prior to using them in various combinations to produce overall concept design proposals. The requirements for each function are given in the following sections together with a list of the alternative solutions considered.

Rigid Hydrofoil Surface

This functional requirement to retain its hydrofoil shape under load, must also provide a smooth surface of good appearance which will resist corrosion, erosion and marine fouling. Solutions considered include

1. rolled steel or aluminium plates, welded and stitYened, dressed smooth, primed and finished withanti-fouling
2. composite foam core sandwich structure with corrosion resistant metal, or reinforced plastic face plates
3. glass reinforced plastic Iayup onto a male former
4. resin and filler skin formed between a male former and a mold
5. foam outer body, formed between an imer skin and a surface mold, finished with sprayed polyurethane elastomer coating
6. outer body built up onto an inner skin using a filler material, and spray coated with polyurethane elastomer.

Hydrofoil Structure

This functional requirement must provide support to the hydrofoil surface to transmit the forces, due to the hydrodynamic loading on the surface, back to the shaft interface. Solutions include:

1. steel or ahuninium webs, hrnes, tubes and sections
2. a solid foam or plastic core material
3. a steel or non-metallic frame to support the perimeter of the surface structure.

Shaft

This functional requirement mustallow transmission of loads from the control surface into the ship via a sealed hull opening. Solutions include

1. a tapered or straight high tensile steel shaft with circular sections throughout
2. a short circuhr steel shaftbonded to a filament-wound reinforced plastic tube inside the control surface
3. a continuous filament wound reinforced plastic tube bonded to an outer sleeve to bear against the seals and bearings within the ship
4. a steel shaft with circular sections in way of the seals and bearings, and square sections in way of the shaft interface
5. a steel shaft with circular sections, welded to a steel box at its outer end.

Shaft Interface

This functional requirement must provide for a rigid connection capable of transferring the torsional, direct and bending forces from the hydrofoil structure to the shaft. Solutions considered include

1. a east steel socket taper orparallel bored to provide an interferenw fit with the shaft, which is retained in position by an end nut, or else shrink fitted
2. a square section tapered steel torsion box running the spanwise length of the control surface, and adhesively bonded or welded to square end sections of the shaft, and also retained axially by an end bolt
3. a parallel or tapered circular hole bored into the solid core of the hydrofoil structure, into which the shaft is adhesively bonded.

Concept Proposals

Six new concept design proposals are devised horn viable combinations of solutions to the four sub-problems described above. These, together with the traditional steel fabrication, are described and evaluated in the following sections, using the design of the prootype roll stabilizer fin as a basis for the evaluation.

CONCEPT NO. 1- STEEL

Basic Form of Construction

As illustrated in Figure 5, webs, frames, root plate and tip plate are welded together, and to a shaft sockeg to form a steel skeleton. Steel skin plates are fillet welded on one side of the fin, and slot welded on the closing side. If required, a cast steel fairing can be welded to the tip of the fin. All surface welds are dressed to satisfy the requirements for surface smoothness. Internal surfaces are coated with an epoxy, and may also be filled by injecting polyurethane foam. The outside surface is shot blasted, primed, painted, and treated with an anti-fouling paint. The shaft is fitted to the tapered, or parallel, bore of the socket with a key, or an interference fit.

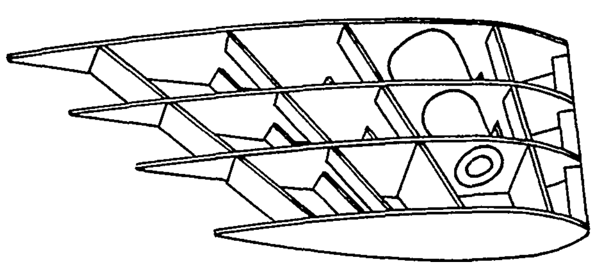


Figure 5. Fabricated Steel Structure

Alternative Approaches

Other metals can be used. For example, using aluminium will result in weight reduction, since material thicknesses are determined by stiffness requirements and corrosion resistance. However, such designs are only used on aluminium craft since the lower cost of steel is otherwise preferred.

It may also be possible to attach skin plates by bonding rather than welding. This allows thinner steel plating to lx. used since there will be less distortion, and also removes the requirement to chess the welds. However, because the webs and frames require flanges to provide sufficient bond area, the total cost is unlikely to be lower.

Discussion

Mild steel structwes are well understood, have a proven track reeord of reliable service, and offer no particukwfabrication hazards. Most shipyards and marine engineering workshops can undertake this type of fabrication so repair facilities are readily available. This concept represents the standard manufacturing method for control surfaces, having superseded steel castings some years ago.

Good surface accuracy can be achieved, but only at a cost of thick skin plates (to reduce weld distortion), closely spaced internal structure (typically 40 times plating thickness), and surface dressing. This leads to both high labor content and a heavy structure. Although the resulting appearance is good, it will deteriorate with erosion and fouling, and is therefore dependent on the performance of paint coatings, which are themselves quickly damaged by cavitation erosion. Surface life is therefore primarily dependent on satisfactory maintenance. Sprayed polyurethane elastomer coatings could greatly improve this situation, and reduce the need for cavitation and corrosion allowances. Both steel skin and core have good impact resistance up to the point at which overall damage owns to the shaft bearings or seal assemblies. The thick plating required for a good surface profile is more than adequate to resist fatigue and hydrostatic pressure loads, while for submarine applications, the control surface can be he flooded to balance hydrostatic loads.

Overall design integrity of the shaft/fin interface is good, provided a socketed design is used rather than a palm end. Shaft to socket joints (either keyed or interference fit) are reliable, and there are no problems in load transfer from socket to fin as a result of the integral nature of the design.

CONCEPT NO. 2- STIFF GLASS REINFORCED PLASTIC (GRP)/FOAM SANDWICH SKIN

Basic Form of Construction

The philosophy behind this concept is that the skin of the fin should be made sufficiently stiff to carry all the hydrodynamic loads without the need for any stiffeners. A simple structure can then transfer the hydrodynamic loads from the skin back to the shaft, as shown in Figures 6 and 7.

The fin/shaft interface comprises a steel box with a web at each end which is welded to the shaft well away from the high stress areas. The box thus encircles the shaft, and provides a large flat area for the bonded interface with the non-metallic structure of the fin. A non-metallic bush with a low modulus of elasticity is fitted where the shaft passes through the root plate, to provide some support without inducing high stresses. The non-metallic supporting structure for the skin is shown in Figure 6. It comprises two main webs, fitted to either side of the shaft box, which extend over the full outreach of the fin. Additional webs are fitted near the nose and tail of the fin, extending between root and tip plates which are cut slightly smaller than the finished section shape of the fin. The webs are bonded to the root and tip plates, with frames fitted between the webs to provide lateral support. A frame may also be required at approximately half span to help transmit the loads. The webs and frames are all cut from a thick (e.g. about 30 mm (1.2 in)) sheet so as to provide a sufficient bond area at their edges. The edges of the webs and frames are cut straight and lie about 40 to 50 mm (1.6-2.0 in) blow the finished surface of the fin such that, when bonded into position, they lie on three plane surhces on each side of the fin forming a land for the flat skin plates.

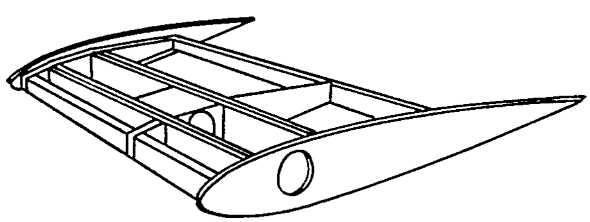


Figure 6. Frame Structure for Concept No. 2

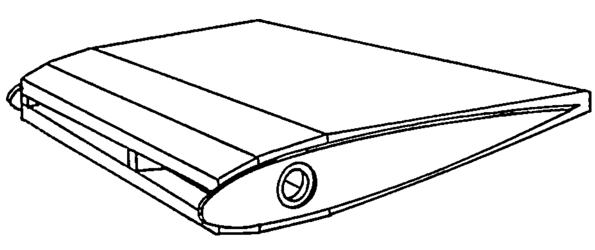


Figure 7. Skin Plates for Concept no. 2

The stiff skin is formed by laying up GRP onto one side of a suitable foam sheet from which plates are cut to fit the three planes on each side of the fin. These plates are then fitted by bonding their GRP skins to the underlying webs, and bonding their edges together. Additional foam blocks are bonded to the nose and tip of the fin. The foam on the skin plates now projects beyond the finished surface of the fin (see Figure 7), and can be cut back to the required shape by guiding a cutter between the root and tip plate sections, such that the cutter always lies along a constant chord line.

After shaping, the foam represents a male former for the fin, slightly smaller than the required size of the fin. A GRP skin is then laid up directly onto this male former.

Alternative Approaches

A sprayed application of the outer skin may be possible. This could consist of chopped glass filaments in epoxy or polyester resin, or possibly polyurethane sprayed onto a glass weave already laid onto the surface. Alternatively, resin injection molding or other vacuum forming techniques could be used with a variety of fiber/resin systems to form the skins. A variety of materials could also be used for the root and tip plates, webs and spacers. These could be cut from PVC sheet, formed from rigid foam, or fabricated as steel sections.

Discussion

An accurate surface profile can be produced without joints, which is smooth enough for practical purposes. Although further data is needed, resistance to cavitation erosion is not expected to be any better than steel, even though subsequent corrosion will not be involved. A sprayed polyurethane coating would give an improved erosion resistance. The relatively thin GRP skin would be subject to damage from localised impact forces, which may lead to water ingress and skin delamination, but minor damage should be easily repaixed. Under general impact or shock loading, the inherent strength will be less than steel, but greater flexibility and localized collapse may prevent serious damage to shaft, bearing and seal assemblies.

The lightweight GRP/foam sandwich struchue will be strong enough to resist moderate hydrostatic and overall dynamic loads provided that all components me designed to resist the applied loads with an adequate factor of safety. Care must be taken to allow for ageing and fatigue resistance of the plastic components, with recommended working stress levels as low as 15% of static strength. There will be no surfeit of strength, as is present in steel structures, but a 10^7 cycle life should be achievable if water penetration is minimized through well-controlled GRP

lay-up and cure. As it is undesirable to free flood such a structure, the design will be limited by depth.

The integrity of the shaft/fin joint is dependent on minimizing stress concentrations by controlling the quality of the welded joint between the shaft and the central steel box. Overall integrity is dependent on the bonds between this steel box, the webs, and the sandwich skin. Large bond areas are possible, so mean stresses should be low, but ctue will be required to avoid stress concentrations at the box comers, where optimum bonded joint design may be difficult to achieve. Although this concept has been used for small scale fins on SWATH vessel (4) it Cannot yet be considered proven technology at larger scales.

The materials involved include steel, plastics, foams, resins, fibers and adhesives. All are currently in marine use worldwide, but special care is needed when handling resins and adhesives. Hand lay-up of w is also labor intensive. Accurate cutting and shaping methods are required for the foam components, and the sandwich core may require a specially designed cutting tool. Accurate assembly will require jigs and clamping systems (e.g. vacuum bags) during adhesive cum. Despite having to cure the resins and adhesives, an overall production time of four weeks should be achievable.

CONCEPT NO. 3- INNER STRESSED SKIN

Basic Form of Construction

A strong steel torsion box runs the spanwise length of the fin and carries the main bending and torsional loads back to the shaft. As shown in Figure 8, steel root and tip plates are welded to each end of the torsion box. They are connected at the leading edge of the fin by a nose bar, and at the trailing edge by a tail bar and a tail plate to form a rigid steel structure. To complete the steel fabrication, thin steel face plates are welded to the structure to form forward and aft void spaces. The shaft, which has a square tapered end section, is socketed into the fabricated torsion box and adhesively bonded into place. The forward and aft void spaces are filled with high density (200 kg/m^3 (12.5 lb/ft^3)) free rise, closed cell, rigid polyurethane foam which acts as a structural component to transmit shear forces. Foam nose and tip blocks are bonded to the steel core structwe which then has surface mold plates clamped around it, while additional polywethane foam is poured into the cavities to take on the finished hydrofoil shape of the fin. Finally the entire surface of the fin is spray coated with polyurethane elastomer to a thickness of 3 mm (0.12 in).

This proposal combines the use of modem materials with conditional steel fabrication so as to separate the load carrying function of the steel structure from the requirement to achieve an accurate and robust surface.

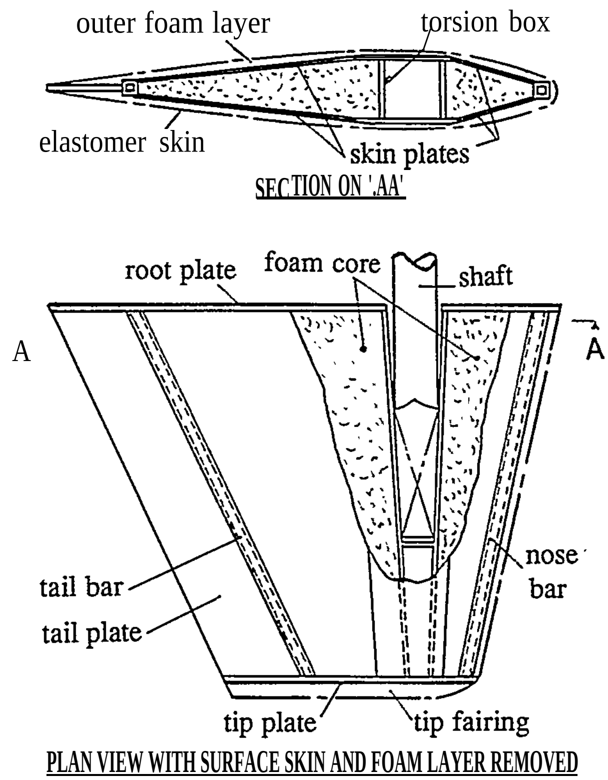


Figure 8. Arrangement for Concept No. 3

Alternative Approaches

The shaft can be welded to the torsion box. The advantage of this is that the close fabrication tolerances required for the adhesively bonded joint between the shaft and the torsion box can be relaxed. However this would be at the expense of the complexity of the structure, and would constrain the choice of materials for the shaft.

The outer layer of foam might be applied by spraying. The foam densities achieved with this process are not as high, and the final surface would be quite rough unless it was machined after foaming. Alternatively, the outer layer might be formed by trowelling on a resin based filler to build up the required surface profile, and provide a harder surface at a penalty of higher cost and mass. Both approaches avoid the cost of mold plates, but suffer similar difficulties of ensuring good accuracy.

Discussion

The labor cost of this structure is low because of the small number of welded parts, requiring the minimum of machining, with no need to dress the welds. Surface accuracy is a function of the rigidity of the mold plates used to resist the pressures created during foaming. High accuracy is possible with a rigid

mold. The polymethane elastomer can be sprayed to a high quality semi-gloss finish which does not require further protective coatings. If sprayed too quickly a mottled surface will result. The elastomer coating is highly resistant to sea water, erosion, fouling and delamination horn its low modulus foam substrate, and is also unlikely to be penetrated by impacts lower than those which would cause damage to the steel substructure. The structure is therefore robust and tolerant of minor defects in the foam. However, local indentation may occur in the foam substrate iiom even relatively low impacts. In such circumstances, the old layer can be patched, shaped and the elastomer skin made good. Absorption into, and penetration of, the outer foam layers by water may well occur if the elastomer skin is damaged, even though the foam is closed cell. More critical, however, is the potential for penetration of water to the highly loaded inner steel/foam interface where deterioration of bond strength may affect structuml integrity. This is an mea where further data is required.

The resilience and flexibility of the structure should attenuate shock loading well, and although the shock capability has not been calculated, it should be possible to design to a specific requirement.

The thin steel clad sandwich structure carries the stresses efficiently, and results in a lightweight fin which should be able to absorb substantial impact before damage is transmitted to the shaft or hull of the ship. Overall integrity of the shaft/fin connection, being mechanically keyed and bonded primarily in compression, is good. The integrity of the fin as a whole is largely determined by the fatigue resistance of the plate welds, the working stress in the foam being only about 0.2 MPa (29 psi). A life of 10^7 cycles is therefore a realistic design criterion. Polyurethane foams are pressure resistant to about 2 MPa (290 psi), but for higher hydrostatic pressures syntactic foams would be necessary.

Although foam and elastomer technologies are new to most shipyards, all materials are readily available, and haveaproven trackrecord in the marine environment. Shrinkage and creep of the foam materials can cause problems during manufacture which require experience to control. Specialized facilities are therefore recommended for foaming and spray coating. This process will take about a week regardless of size; one additional week is required for surface curing. The main activity is the steel fabrication which, except for the tolerance control of the torsion box, is conventional. Depending on size, this suggests an overall production time of four to six weeks.

CONCEPT NO. 4- SOLID SYNTACTIC FOAM

Basic Form of Construction

As shown in Figure 9, one or more solid large blocks of prefabricated syntactic foam with a density

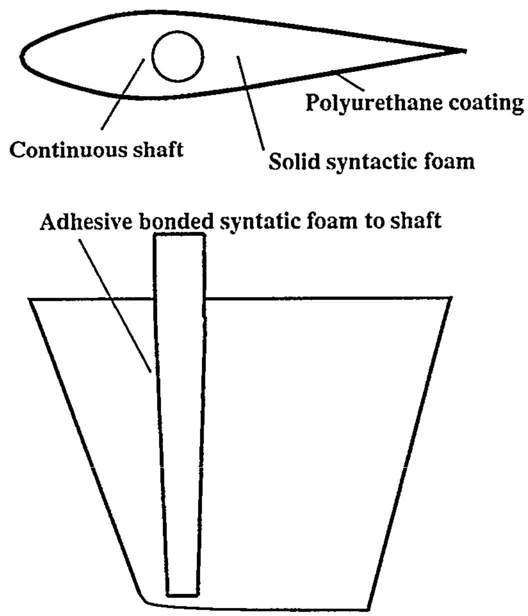


Figure 9. Arrangement for Concept No. 4

of about 700 kg/m^3(44 lb/$ft^{3)}$ are bonded together and then profile machined to the required fin shape. The shaft is then bonded into a bored hole, extending to the tip of the control surface in order to carry spanwise bending loads. A flexible polyurethane elastomer coating is applied to appnximately 3 mm (0.12 in) thickness to form the surface skin.

Discussion

The overall structure is relatively ligh6 despite the need for a full span shaft, and is also simple to fabricate, with low labor costs. Syntactic foam can be easily machined using carbide tools to give an accurate surface shape but, as the polyurethane coating will reproduce the surface texture of the foam, high resolution machining is required for good surface appearance. The general performance of the elastomer coating is the same as for Concept No. 3.

There is extensive experience of syntactic foam used to resist hydrostatic loading to depths of 2000 m (6560 ft), and this concept has an estimated safety factor of four against failure under the casualty load. There is little data on fatigue performance of syntactic foams, but performance is expected to be kiter than fiber reinforced composites, and a 10^7cycle fatigue life should therefore be readily achievable. Bonding tests between steel and syntactic foam adherents using cold cure epoxy adhesives indicate that joint strength is limited by the strength of the foam. The shaft to fin joint, and overall fin integrity are therefore limited by the strength of the foam, which may fracture or crush under shock or localized impact respectively.

Full repair capabilities are not yet available on a world-wide basis.

Although in regular use for high pressum buoyancy, syntactic foam is a new material for most control surface manufactures. It can either be purchased as blocks or foamed in house. Cutting and shaping present no particular problems. Polyurethane elastomen, on the other hand, are best sprayed by specialist subcontractors who can better deal with the hazards. Overall production time is the to six weeks once the foam blocks are available. Exothermic reactions during cure limit the size of blocks and speed of manufacture. Large fins must be built up by bonding layers of blocks together.

Syntactic foam has been used in French Navy designs for hydroplanes, and has also been recommended by a design study on non-metallic hydroplanes undertaken by the British Navy (l). Both these designs employ a resin or GRP skin, and require the use of a mold. However, for near surface applications, this concept is only cost effective for smaller control surfaces because of the high cost of syntactic foam.

CONCEPT NO. 5 - GRPAND FOAM

Basic Form of Construction

A prefabricated GRP filament wound tube is bonded over the end of a short shaft to form an extended shaft. This extends to the tip of the fin, and the fin is fabricated around it as shown in Figure 10.

A GRP plate, with a sealing joint around the shaf4 is fitted at the root. Foam blocks of low density (120 kgJm^3(7 lbs/ft?)) are bonded onto the inner support in the lower stress areas, whereas syntactic foam is applied in the higher stress areas such as the nose. Finally, the foam is shaped and GRP is laid up to form the outer skin.

Discussion

The performance of the GRP skin is as described for Concept No. 2. The general peformance will be similar to that described for Concept No. 4, but the improved load carrying capabilities of the GRP skin provides better resistance to external loads, impact and shock, although the presence of polyurethane foam will reduce the capacity to withstand hydrostatic loads. The performance of the filament wound GRP shaft, and its bonds to the steel shaft, would need to be proved by prototype testing, although a small angle machined scarf joint appears to be both practical and effective. The resulting structure is lightweight, and relies on technology fairly well understood within the marine industry. However, the large number of components requiring careful surface preparation for bonding implies some additional machining and labor costs, although resin injection systems may be able to minimize the GRP lay-up costs.

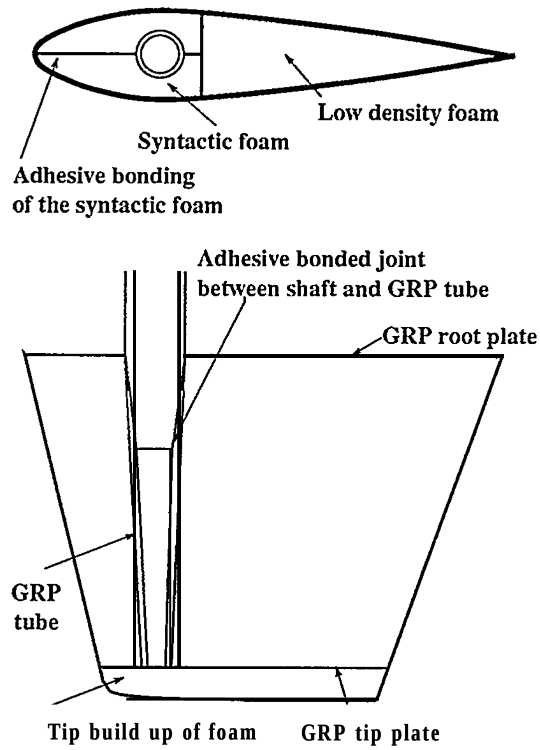


Figure 10. Arrangement for Concept No. 5

CONCEPT NO. 6- CORED OR HOLLOW CASTING

Basic Form of Construction

The fin is cast within a female mold, which provides the required finished external shape. The mold is held vertically with the tip down and the root uppermost, so that the casting material can be poured into the mold around the shaft and cores, which are suspended in place as shown in Figure 11. V'ous materials can be used for the casting, but for this concept description nylon 6 has been selected, as there is a significant amount of experience of its use in large castings.

The shaft is forged into a spade end to ensure that it is securely keyed into the fin, so that the torque will be effectively transmitted, and to allow a sufficient depth of material between the shaft and the surface of the fin. The cores are designed to provide uniform thickness of the cast material, and to minimize residual stress concentrations caused by the shrinkage of the cast material as it cools.

Although a mold is required, a master mold could be used to produce a range of fin sizes to a standard profile by inserting a tip mold as a lower dam, and then pouring the mix to the required depth. To reduce stress concentrations, the cores should collapse easily to accommodate shrinkage of the mix as it

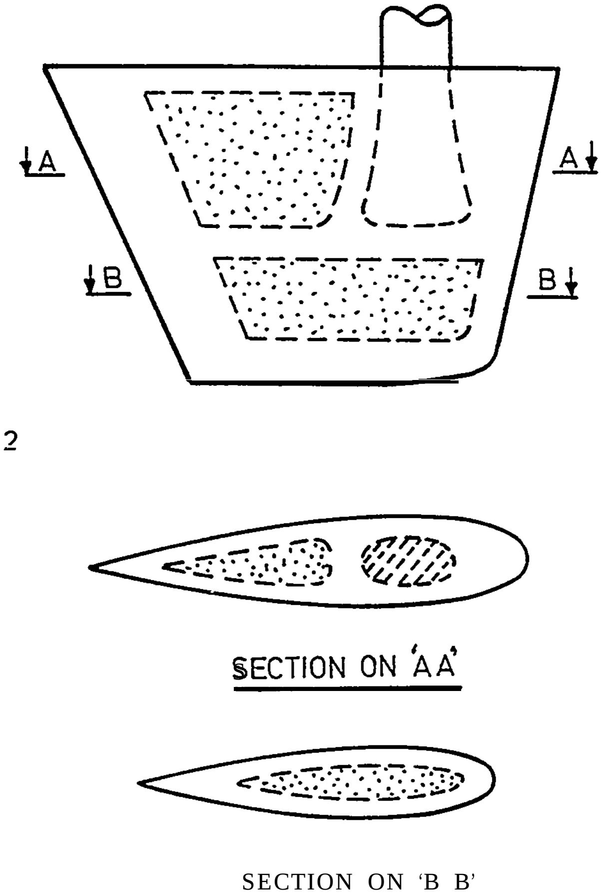


Figure 11. Arrangement for Concept No. 6

cools. It would also be an advantage if a method could be devised whereby a thin compressible coating is applied to the spade shaft, as this would allow the shrinkage to take place without inducing high residual stresses at the shaft interface. The casting should be annealed to further reduce residual stresses.

Alternative Approaches

A range of other plastic materials can be considered instead of nylon 6, and it may be possible to consider using machined flats on the shaft rather than a forged spade. At the other extreme, if weight is not a problem, metal castings can be used.

Discussion

Cast nylon offers a lightweight solution with high surface accuracy, good self-colored appearance, and low labor costs. It is widely used in the marine industry, and is used for small fin stabilizers as a solid casting (Concept 7). Although it absorbs some water, this dcxx not appear to be detrimental. Erosion and fouling resistance are goo& although not as good as polyurethane elastomer. However, general resistance to impact is less certain as there seems to be a threshold above which the material may split or shatter. Despite this, the body of the casting should withstand shock loads due to its inherent flexibility, although the behavior of the shaft/fin interface is less certain. Provided that the wall thickness of the nylon is huge, there are good margins of strength against static, hydrostatic, and fatigue loads, although the effects of ageing and fatigue require that the fin should operate at low stress levels to achieve a life of 10^7 cycles.

Overall design integrity appears to be good, particularly with a shaft interface based on a spade or flats machined on a circular shaft. Unpublished test results suggest the bond of nylon to steel is as strong as the nylon itself. The main area for concern remains the reduction of residual shesses in nylon after casting, which are a potential risk if further machining is needed as the material may shatter. This problem requires further research.

Cast nylon 6 is readily available, but generally only in casts of up to about 500 kg (1100 lb). Larger sizes would require extensive capital investment which would relegate its use to specialist subcontractors. The major advantages of this concept are its light weight and its potential low cost once the mold is made, although the concept becomes relatively expensive in large volumes. However, uncertainties remain over the problems of stress concentrations around the embedded shaft, and the behavior of the material under large impact loads, and after ageing.

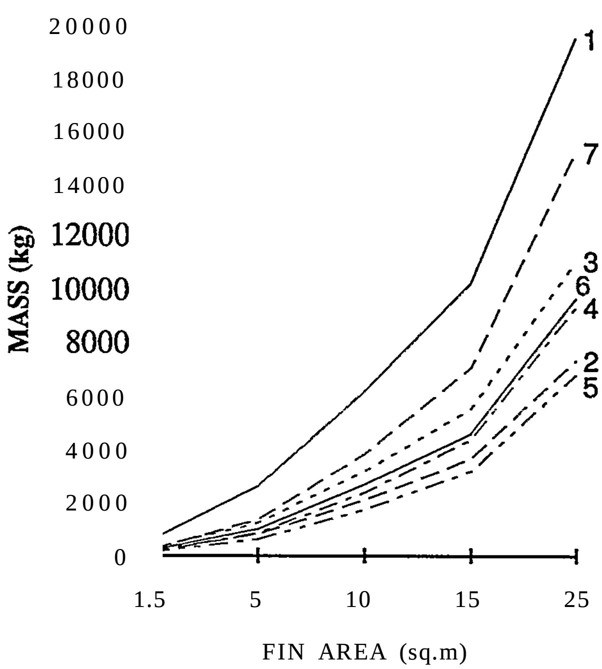


Figure 12. Mass of Fin Concepts

	CONCEPTNU.BER						
	1	2	3		5	6	7
EVALUATION CRITERIA				RANKINGS			
Accuracy of surface	7	5	3	4	5	1	1
Appearance of surface	5	6	3	4			
Resistance to erosion		5	1		2	1	1
Resistance to fouling	7	5		1	5	3	3
Resistance to seawater		6	4	3	5	*1*	*1*
Skin impact resistance	7	6		2	6	4	4
General resistance to impact	*1*	5	2		6		3
Static loads	*1*	5	4	7		3	2
Fatigue loads	*1*		4	7	3	3	2
Shock loads		5			6	***3***	2
Life	*1*		4	5	6	***2***	2
Shaft joint integrity	*1*	5	2	6	7	4	5
Overall design integrity	*1*	3	2	6		5	4
Materials track record	*1*	*1*	2	2	3	3	***1***
Manufacturing methods	*1*	2	3	3	3	4	***4***
Mass (ex. shaft) (kg)	581	150	240	141	107	186	224
(lb)	1278	330	528	310	235	409	493
Hydrostatic depth (m)	>5000	50	100	3500	150	50	3000
(ft)	16400	164	328	11484	492	164	9843
cost - fin and shaft	27627	$4530	s 4410	25865	56445	$ 2850	$ 3850
	$11974	$7112	$6924	$9208	$10119	$4475	$6045
- *fin* only	S 5857	S 3250	$3130	f4195	**£ 5215**	**£ 1500**	**£ 2500**
	$9195	$5103	$4914	$6586	$8188	$2355	$3925
Fin material cost	S 732	2450	s 400	52175	$ 1535	**£ 0**	
	$1149	$707	$628	$3415	$2410	***$ 0***	**$ 0**
Fin sub-contract cost	5225	20	s 500	$ 500	f o	**£ 1500**	**£ 1800**
	$353	*$0*	$785	$785	$0	**$ 2355**	$2826
Fin labor hours	178	100	74	48	128	0	20

Table IL Concept Evaluation

NO. 7- SOLID CASTING

Basic Form of Construction.

The requirements for a mold are as for Concept No. 6, but the material is cast solid without cores, and without the shaft in place. The casting is then bored to accept the shaft which can be adhesively bonded and retained axially. This method is included as an alternative to Concept No. 6 because it is currently used for the production of some small stabilizer fins. The advantages and disadvantages are much the same bug because cores are not included, and kecause the shaft has to be fitted, the mass and the cost are higher.

EVALUATION OF DESIGN CONCEPTS

The concept design proposals are evaluated against each of the evaluation criteria on the basis of the standard 1.5 m^2 (16 ft^2) roll stabilizer fin. The level of design detail available for the evaluation is of necessity quite low due to the number of concepts considered, and an element of subjective judgement is involved. It is therefore important not to place too much reliance on absolute values, but to use the figures mainly for comparisons. The results are summarized in Table IL The estimates of mass for each concept are plotted against fin area in Figure 12. The cost for each of the seven concept designs, broken down into labor and material cost for the fin itself plus a total cmt for the shaft is plotted in Figures 13 to 17 for the five different fin sizes considered.

Performance.

The performance requirements relate to the mass of the fin, the accuracy of the surface, and its resistance to the environment. The mass is lowest for foam structures without any significant steel elements, but their structural integrity is not well established, so

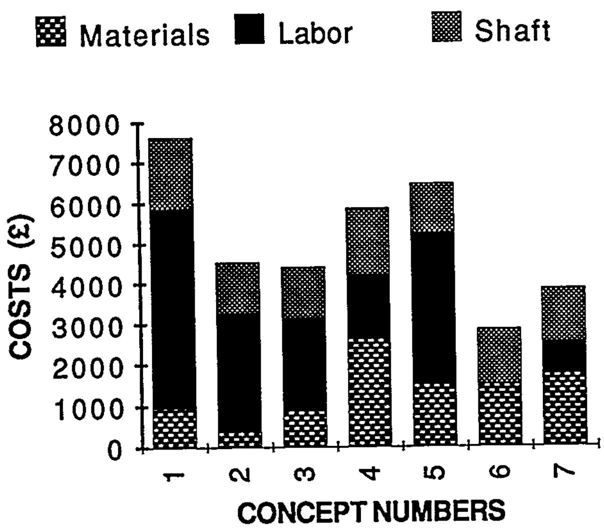


Figure 13. Costs for 1.5 sq.m Fin

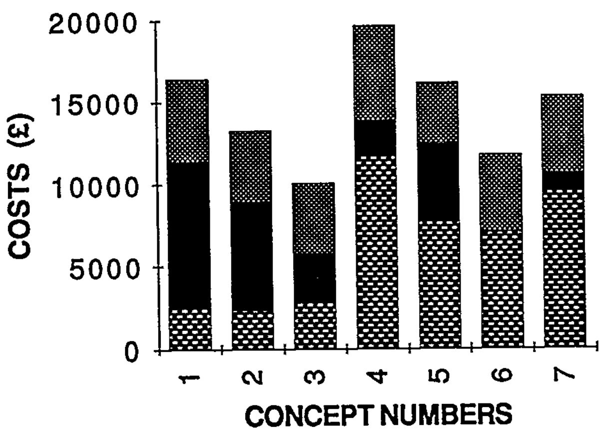


Figure 14. Costs for 5 sq.m Fin

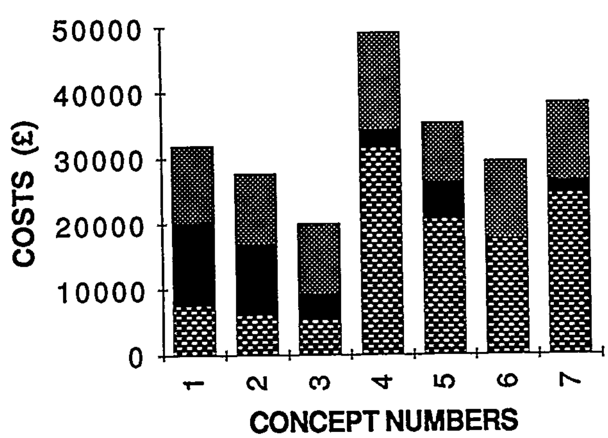


Figure 15. Costs for 10 sq.m Fin

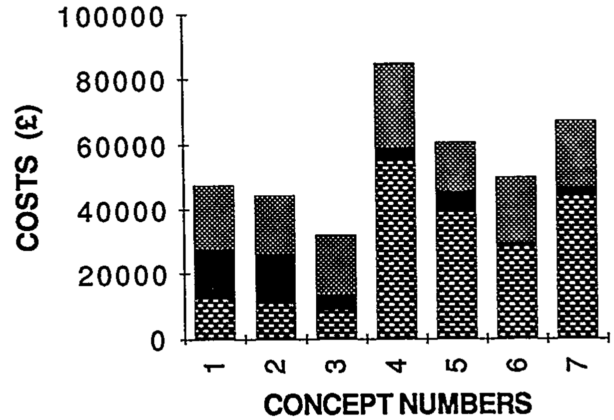


Figure 16. Costs for 15 sq.m Fin

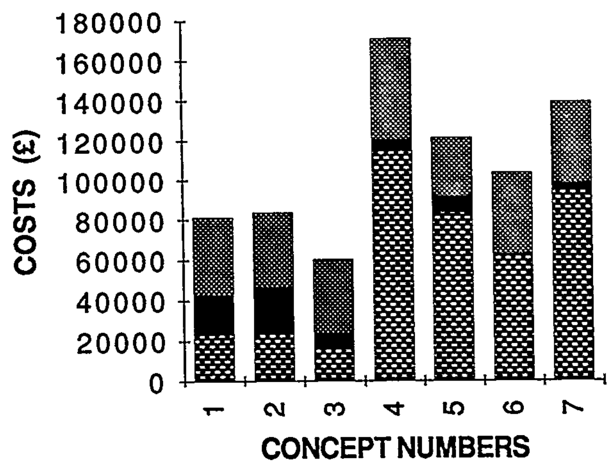


Figure 17. Costs for 25 sq.m Fin

Concepts 3 and 4 are preferred, even though their mass is higher. The cast nylon designs have low mass at small sizes, but this is not sustained as size increases. The best surface accuracy is achieved by the use of the full molds as in Concepts 6 and 7, with the mold plates of Concept 3 coming next. The sprayed polyurethane elastomer coating provides the best resistance to the environment. This can, of course, be applied as a surface finish to any of the concept designs, but with a low modulus foam substrate the risk of delamination of the coating under impact and cavitation loading is much reduced (5).

Strength

All the concepts are designed to carry the required loads, and to survive the specified life. The scantlings of the traditional steel construction are determined mainly by the requirement to avoid distortion, and to provide a corrosion allowance. The strength requirements

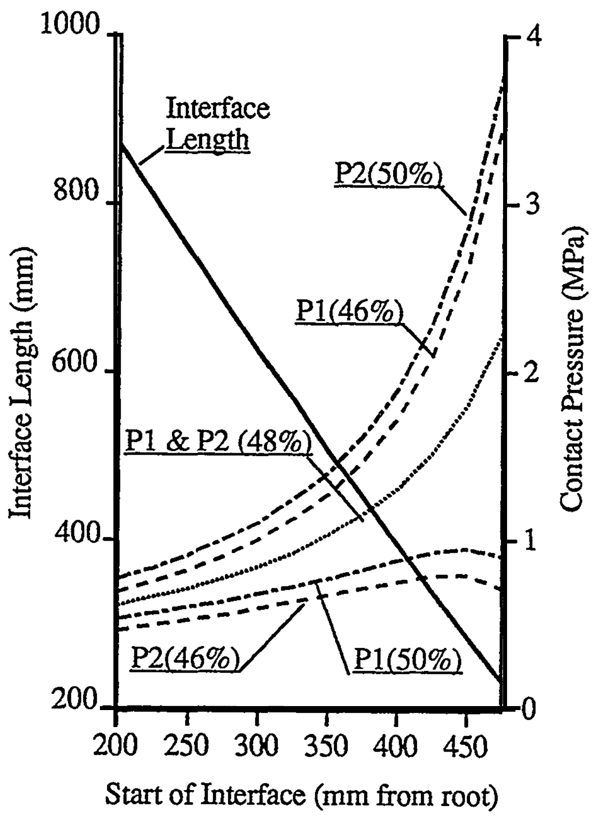


Figure 18. Contact Pressure at Shaft/Fin Interface

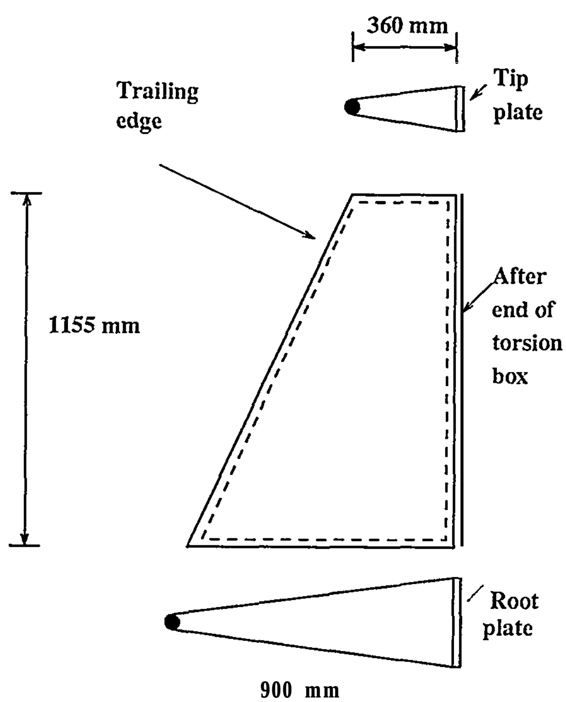


Figure 19. Sandwich Panel for 3D Analysis

foam and in the steel structure. A sandwich panel (see Figtue 19) representing the foam-filled structure between the aft side of the torsion box and the trailing edge of a 1.5 m^2(16 ft^2) fin is analyzed with a number of different foam densities. The face plates of the sandwich are 3 mm (0.12 in) mild steel, while the root, tip and torsion box plates at the boundaries of the panel are all 10 mm (0.4 in) mild steel. A steel tube (outer diameter 35 mm (1.4 in), wall thickness 5 mm (0.2 in)) is welded between the tip and root plates, and ties tie top and bottom skin plates together at the trailing edge. The maximum thickness of the sandwich is 190 mm (7.6 in) at the root end closest to the torsion box, and the minimum thickness is 35 mm (1.4 in) at the trailing edge. The boundary condition for the analysis is that the face plates are fixed at the torsion box.

The load applied to the structure has a non-uniform pressure distribution. This is based on a triangular distribution of suction pressure on the upper side of the model, and a uniform distribution of pressure on the lower side, giving an equivalent total vertical reaction force of 66 kN (6.62 tonf) if applied to the entire fin surface. This corresponds to the maximum working load of the fin without safety factor, Both the foam and the steel are assumed to be isotropic, and to have linear elastic properties.

Calculations are carried out with foam densities of 100, 150 and 200 k~m^3(6.2, 9.4, 12.5 lb/ft^3). The foam used is a rigid closed cell polyurethane foam for which elastic modulus and density may be related to the properties of solid polyurethane by the equation given by Gibson and Ashby (6).

$$\frac{E_f}{E_s} = \varphi^2 \left(\frac{\rho_f}{\rho_s}\right)^2 + (1-\varphi)\left(\frac{\rho_f}{\rho_s}\right) \qquad (4)$$

where Ef is the elastic modulus of the foam, Es is the elastic modulus for the solid material (1600 MPa (232000 psi)), ρ_f is the foam density, and ρ_s is the density of the solid material (1200 k~m , (74.88 lb/ft^3)). (p is the fraction of the volume of the polymer material that is contained within the cdl edges. Vidues given for this vary from 0.6 to 1.0, the latter value being used for this analysis. Poisson's ratio for the foam is assumed to be 0.25.

The analyses show a stress concentration in the steel face plates at the attachment points to the torsion box. The reason for this is that, at distances greater than about 100 mm (4 in) from the attachment points, the sandwich panel acts as a composite structure, with the foam core carrying the shear forces, and the face plates carrying the direct forces. Closer to the attachment points the face plates are held at a fixed distance apart by the stiff structure of the torsion box. As only small deformations can cccur in the core material at this poing the foam does not carry much shear force, and the face plates behave largely as two separate plates with a consequent increase in stress. However, the maximum stress at the attachment point still varies with the foam density as shown in Figure 20. The

are easily satisfied, with the only disadvantage being that the rigidity of the design will tend to transmit impact forces direct to the shaft rather than absorb impact energy through distortion of the fin structure. The strength requirements can be easily met with the nylon castings, and in Concept 3 the steel frame and inner skin can be sized to carry the main loads so that the design is more tolerant of defects in the foam than those in which the foam is the principal structural element. There is some concern about fracture under impact loads of the solid nylon or foam designs when there is no GRP or steel outer skin.

The steel fabricated fin can withstand high hydrostatic pressures if it is flooded, while the nylon and syntactic foam have sufficiently high compressive strength to withstand high pressures as solid bodies. Syntactic foam could also be used with Concepts 3 and 5 to give a good hydrostatic depth capability.

Manufacture

Marine engineering companies and ship repair yards are mainly equipped to handle metal products, so the introduction of non-metallic composites would require investment in new facilities and in training, or the sub-contract of significant parts of the manufacture. Polyurethane foams, elastomers and GRP are all currently used in marine applications, and companies exist that can handle this sub-contract work. However, the technology is not complex, and the plant required is not excessively expensive, so it is a realistic proposition for a company to re-equip for a new method of manufacture. The steel fabrication contained in Concept 3 allows a good element of in-house work while still sub-contracting the polyurethane work.

Cost

Figures 13 to 17 show the shift in the balance of the costs as the fin area changes. The advantage of the solid cast foam or nylon fins at the smaller sizes is soon lost as the material cost outways the labor cost when size increases, since the mass of material varies with the cube of scale. Concept 3 establishes and maintains a consistent cost advantage at 5 m^2, (54 ft^2) size and above.

SELECTION OF PREFERRED DESIGN

In terms of strength, the steel fabrication holds a clear advantage, but the evaluation shows that savings can be made in cost and mass, and that improvements in performance can be realized. The cored cast nylon Concept 6 shows clear advantages at the smallest size, and cast nylon fins are already being produced at this size. However, over the full range of sizes, the best potential is offered by Concept 3, which has low cost, offers good reductions in mass, and provides the benefits of the polyurethane coating. The integral steel core fabrication allows this concept to be viewed as less radical than some, in that it provides reassurance in terms of strength capability, and in terms of familiar manufacturing processes.

DEVELOPMENT OF THE SELECTED DESIGN

Further work has been carried out on Concept No. 3 to establish its feasibility, and to obtain more accurate estimates of mass and cost. Areas of the design that have been studied in more detail follow.

Shaft Interface

The options to consider are a shaft with either circular sections bonded, or shrunk fit, into a tapered, or stepped, socket, or with tapered square sections bonded to a fabricated steel, torsion box. The latter option is attractive since the costs of casting and boring a circular socket are avoided, but difficulties with fabricating a square socket to the tolerances required for a bonded joint leads to serious consideration of the circular shaft. However, successful weld tests show that the required tolerances can be achieved and the square section fabricated torsion box has been adopted for design development.

The torsion box is designed with a three degree taper to match that of the surface of the fin, and the square sections of the shaft are machined to this same taper. The spanwise location of the interface between the torsion box and the shaft is selected so as to minimize the bending moments in the torsion box, and also to ensure that the external loads on the fin can be transferred to the shaft via a uniform contact pressure over the interface area, i.e. the pressure at one end, p_1, is equal to the pressure at the other end, p_2. The design is based on an assumed spanwise center of pressure of 48% of the span. However, this position is not accurately known, and may vary between 46% and 50% of the span, with a resulting change in the pressure distribution over the length of the shaft interface. Figure 18 shows the contact pressure at each end of the shaft interface plotted against the spanwise location of the start of the shaft interface; three possible positions of center of pressure are presented. The left-hand scale shows the required length of interface to ensure that $p_1 = p_2$ when the spanwise center of pressure is 48%. A start position of 400 mm (16 in) from the fin root is chosen to ensure a small variation of maximum contact pressure with changes in spanwise center of pressure. The required length of interface is then 394 mm (15.8 in).

Composite Beam Design

A three-dimensional finite element analysis is performed to enable the foam density to be selected on the basis of its influence on the stresses in the

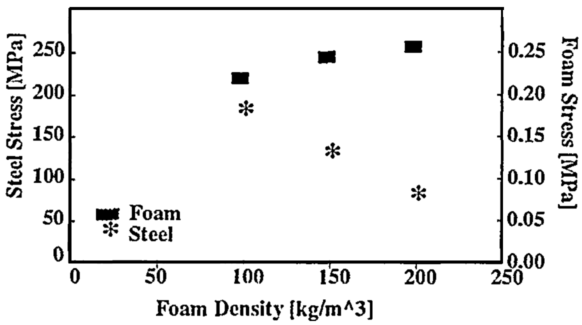


Figure 20. Maximum Stresses in Steel and Foam

figure also shows the maximum shear stress in the foam. This rises with increasing density because as the foam becomes stiffer, it carries more of the load.

On the basis of these results, a foam density of around 200 kg/m^3 (12.5 lb/ft^3) is selected, although further design work as described in the next section, is required in order to reduce the stress levels in the steel. The maximum shear stress of 0.26 MPa (37.7 psi) results in a good factor of safety against the theoretical shear strength of about 1.7 MPa (247 psi) derived from Gibson and Ashby, although tests on actual samples of foam with this density gave a shear strength of only 1.1 MPa (160 psi).

Torsion Box to Skin Plate Transition

The cantilever sandwich of steel/foam/steel is very efficient in carrying loads, but difficulties arise as the face plates approach the torsion box. Here they appear to act as two separate unsupported cantilever beams with a very rapid increase in stress. To obtain good fatigue performance it is important that stress in the welds is kept low. The main requirement is to establish additional stiffness in the transition region which extends some distance beyond the torsion box before the foam core fully supports the sandwich structure.

A number of different design solutions for the local steel structure are analyzed using the finite element method. A section at mid-span of the fin stabilizer is chosen for analysis. The displacement and the twist angle for the section are determined using three-dimensional analysis, and then used as boundary conditions for the four comer nodes of the torsion box. The load applied to the model is the non-uniform pressure distribution described earlier, but in this case the loading is equivalent to a total lift on the full fin of 137 KN (13.75 tonf). This represents a factor of two on the maximum design working load. The torsion box material, and that of the face plates of the sandwich structure, is mild steel, while the core material is polyurethane foam with a density of 210 kg/m^3 (13.1 lb/ft^3).

Two approaches to increasing the stiffness in the transition region are examined. First, the top and bottom plates of the torsion box are extended forward and aft, tapering over various lengths from a thickness of 10 mm (0.4 in) down to the 3 mm (0.12 in) required for the butt weld to the face plate. The second approach is to further stiffen the transition region by adding open triangular steel sections to the front and back of the torsion box, which extend into the foam, thus reducing the depth of foam in the transition region and increasing local stiffness.

The results of the analysis of these arrangements are presented in Figure 21. The plots show the direct stress acting in the chordwise direction on the top and bottom surfaces of the top and bottom face plates. The stress reversal across the thickness of the face plates in the region close to the torsion box shows that they are acting as independent beams, rather than a composite structure. The arrangement in Case c) gives the lowest stresses in way of the weld, and is adopted for the final design.

Analysis of Total Structure

With the required foam density found and tested, and the final design of the shaft and torsion box decided, a three-dimensional finite element analysis of the full inner structure of the 1.5 m^2 (16 ft^2 fin is carried out.

The model comprises 10mm (0.4 in) mild steel torsion box, root and tip plates, 3 mm (0.12 in) mild steel face plates, and 200 kg/m^3 (12.5 lb/ft^3) density foam core. The shaft interface extends from 400 mm (16 in) to 794 mm (31.8 in) from the root, and the model is fixed at the shaft where it passes through the root plate. The load applied to the structure is a suction load on the upper surface and a pressure load on the lower surface, with an approximately eliptical spanwise distribution, giving a center of pressure at 48% of the span. The total normal load in this analyses is 66 kN (6.63 tonf), representing the maximum normal working load.

The primary requirement of the analysis is to check the stress range in the various welds when the load changes between pressure and suction, as a result of a reversal in the angle of incidence of the fin to the water flow. The stress ranges are calculated by taking the difference between the stresses at corresponding nodes in the top and bottom plates. Since the top plate is loaded in suction and the bottom plate in pressure, the difference between them gives the design stress range under fatigue loading. Figures 22 and 23 show the stress range in the welds between the sandwich face plates and the forward and aft extensions of the torsion box plates. The stresses are given as direct stresses in the chord wise direction on the inner sides of the face plates, where the stress ranges are at their highest, The maximum stress range in a weld is approximately 65 MPa (9425 psi), which satisfies the requirement for a butt weld to achieve the target fatigue life of 10^7 cycles.

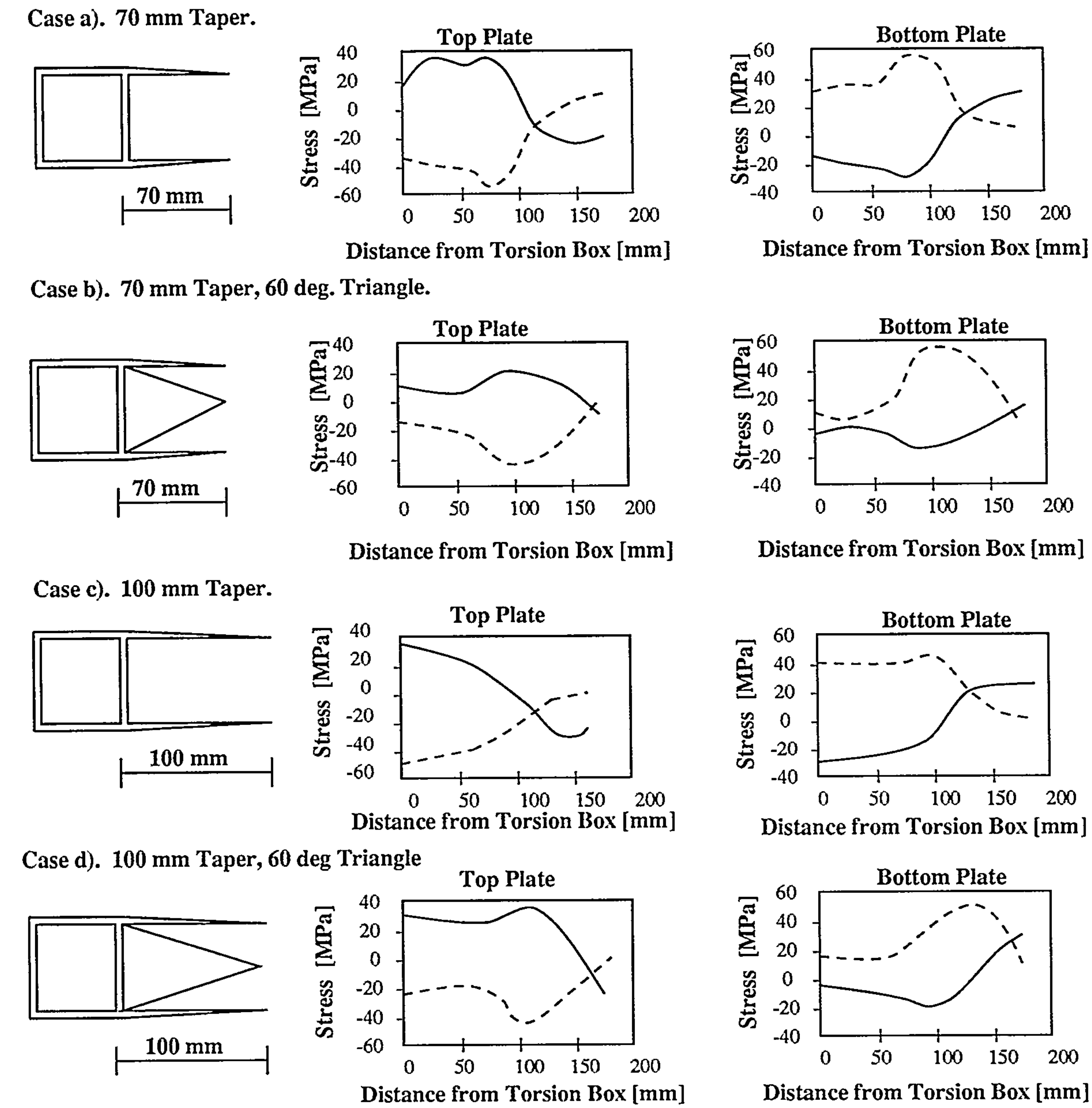


Figure 21. Stresses at Face Plate/Torsion Box Interface

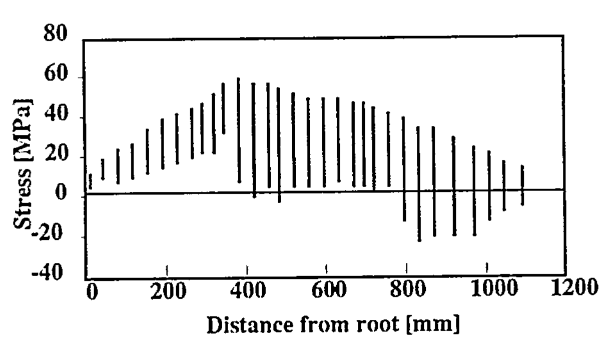


Figure 22. Stress Range in Weld for'd of Torsion Box

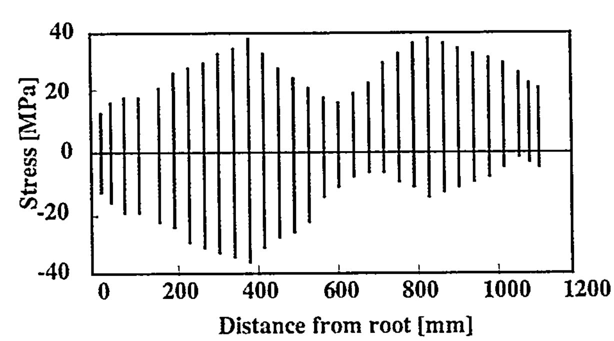


Figure 23. Stress Range in Weld aft of Torsion Box

Estimate of Mass

The detailed estimates give a total mass of 250 kg (550 lb) for the 1.5 m^2 (16 ft^2) fin, comprising 203 kg (447 lb) of steel work, 35 kg (77 lb) of foam, and 12 kg (26 lb) in the elastomer coating. This gives a 56% reduction in mass relative to the fabricated design, against a target reduction of 25%.

Estimate of Cost

The detailed estimates give a total cost for the 1.5 m^2 (16 ft^2) fin of £3900 ($6123), made up of £555 ($871) in material costs, and £3345 ($5252) in labor costs with overheads. This represents an estimated saving of 34% of the cost of the fabricated fin, against a target saving of 40%.

CONCLUSION

The conceptual design study identifies the requirements for hydrodynamic control surfaces, and shows that these can be met by a number of designs based on the use of composite materials as an alternative to the traditional steel fabrication. The concept designs are evaluated against a set of pre-defined criteria, and Concept No. 3 is selected as the design that provides the best alternative to steel fabrication. This design is developed in more detail in the form of a ship roll stabilizer fin with an area of 1.5 m^2 (16 ft^2). It offers the potential to reduce the cost of the fin itself (excluding the shaft) by 34%, and the mass by 56%, while also providing a more accurate and smooth surface that has better resistance to erosion, corrosion and marine fouling. Further work has been completed on the selected design to produce a detailed design procedure, and to build and sucessfully test the 1.5 m^2 (16 ft^2) prototype stabilizer fin. This work will be reported in future papers.

ACKNOWLEDGEMENTS

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REFERENCES

1. Unpublished design studies by the British and French Navies.
2. Abbott, I.H. & Doenhoff, A.E., The Theory of Wing Sections, Dover Publications Inc., 1959.
3. Chalmers, D.W., "Experience in Design&Production of FRPMarine Structures," Marine Structures 4,1991.
4. Fairlie-C1arke, A.C., "Design & Construction of Fin Units for SAMHACH," Glasgow Marine Technology Centre Report No. 91-04.
5. Angell, B., Long, R.F., Weaver, W.B. & Hibbert, J.H., "Cavitation Resistant Coatings for Naval Use," Proceedings of 5th. International Conference on Erosion by Solid and Liquid Impact 1979.
6. Gibson, L.J. and Ashby, M.F., Cellular Solids, Structure and Properties, Pergamon Press, 1988.

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An Engineering Product Model Based on STEP Protocals

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ABSTRACT

Draft STEP application protocols, developed by the Navy Industry Digital Data Exchange Standards Committee (NIDDESC), have been issued to define the information content of a product model for a ship. The work reported in this paper combines the existing CAD models of the DDG51 Class design with a newly-developed non-graphic database so that the overall information content complies with the STEP protocols. This work represents the first-time implementation of the application protocols and is a significant step in the Navy's plan to do the design of variants of the DDG51 Class totally in CAD. The combined graphic/non-graphic database is referred to as the DDG51 engineering product model. Emphasis has been placed on populating the non-graphic database with the information necessary to perform all required engineering analyses. The basic schema described in this paper may be extended to support other areas of interest, such as logistics support.

BACKGROUND

The U.S.S. Arleigh Burke (DDG51) Class of AEGIS Destroyers represents state-of-the-art technology, and is replacing retiring fleet assets as a vital part of the Navy's smaller, more capable fleet. The design and construction of these warships also feature the application of state-of-the-art technology. As a cost saving initiative and quality improvement measure, the Navy has implemented the use of 3-D Computer Aided Design (CAD). This effort required the development of leading edge CAD technology and the achievement of a cooperative (rather than competitive) success story by the two DDG51 Class shipbuilders and other industry participants.

Over 2,500 drawings, many of which contain over 30 sheets per drawing, are required to build an AEGIS destroyer. Maintaining an error free design baseline defined by these drawings has proven to be a challenge in a 2-D manual environment. To improve efficiency, the entire design is being converted to 3-D CAD. The DDG51 design consists of 77 design zones. A 3-D computer generated representation of each of these zones is being developed. These models contain library parts defining equipment and machinery arrangements, structure, ventilation, electrical, and piping distributive systems.

Library parts are 3-D geometric representations of ship components, and contain maintenance and access clearance requirements as well as attribute information. These parts are constructed once and used many times throughout the ship design. Construction of library parts and zone models is governed by program standards defining content requirements. These are based on actual ship design and

construction needs. A CAD model for one of the construction zones for the DDG51 Flight I ships is shown in Figure 1.

Once generated, the 3-D models offer several advantages in enhancing the shipbuilding process. Simultaneous visualization of all disciplines located within a compartment enables concurrent, rather than sequential, system design. With the added feature of dimensional accuracy inherent in CAD geometry, arrangements can be optimized before the first piece of steel is cut. The need to construct costly full scale mock-ups is therefore eliminated. CAD models are also valuable tools for fleet training applications.

For production use, interference and interface problems that were traditionally not detected until actual construction can now be resolved prior to the release of construction documentation to production trades. Interference free/interface correct construction drawings are generated directly from the model. In addition, numerical control data for fabrication of ventilation and pipe is generated directly from the model. For life cycle support, a model representing the as-built configuration delivered to the planning yard will support maintenance and modernization tasks over the ship's forty year life.

To succeed in this effort, the program first had to overcome the incompatibility between CAD systems used by the two different ship construction yards. Sharing data between their ComputerVision

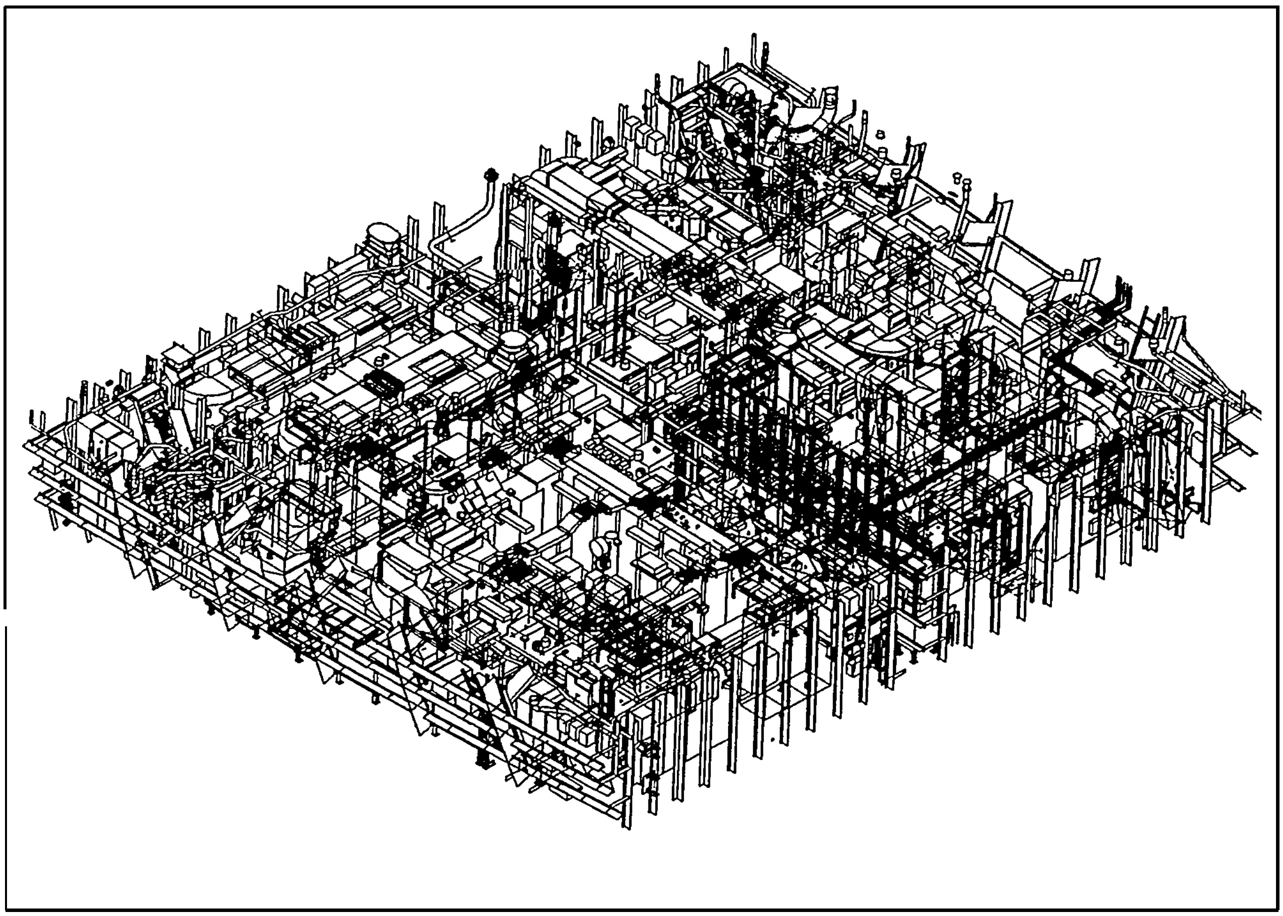

FIGURE 1. DDG51 CAD model.

and Calma systems was not feasible using commercially available software. The Navy elected to develop a translator to exchange ship design information between the yards. This translator required that information exchanged first be processed into a neutral file before receipt by the receiving shipyard. This option provided flexibility for software maintenance, facilitated development of translators to additional CAD systems and most importantly allowed each shipbuilder to continue “business as usual” with the CAD systems already in place at each facility. The use of these software routines is now referred to as the DDG51 Digital Data Transfer (DDT) process (l). In order to formalize and standardize the data transfer process between the shipbuilders, the Navy issued a DDG51 CAD model transfer specification (2), in which the information content of the CAD models was defined.

Development of a standard translator allowed a cost effective transition to 3-D CAD. The task to convert the design to 3-D was shared between the shipbuilders. Data was exchanged via the translators; this eliminated any duplication of effort and also reduced the total time required to convert the design.

One of the most significant uses of the 3-D models will be to support design and construction of the next generation of AEGIS Destroyers, DDG51 Flight IIA. This design features the addition of a helicopter hangar. These ships are to be the first Navy ships designed and engineered totally in CAD. The CAD models will function as electronic baselines to accurately design the modifications. Applying concurrent and human factors engineering will be key factors in attaining the Navy’s goal of reducing the acquisition costs of AEGIS destroyers.

Among the categories of data to be included in the models are geometric-type data (entity coordinates and orientations), connectivity data (where applicable), and some limited object-oriented intelligence. This latter category includes run designations for distributive systems and shipbuilder-defined stock or catalog numbers for individual objects. It is this intelligence category of information which distinguishes the DDT translators from other geometric-entity translators, such as Initial Graphics Exchange Specification (IGES) translators; it formed one of the buiIding blocks for developing an engineering product model (EPM).

During the development of the DDG51 CAD model specification and DDT translators, work was begun on the formal definition of a digital product model for a ship. This work was conducted by NIDDESC, a joint Navy/marine industry effort to draft application protocols (standards) for a breakdown of a ship and its components. The NIDDESC standards will be a part of the STEP (Standard for the Exchange of Product Model Data) international standards. The work of the NIDDESC Committee and a description of the draft standards were presented to the 1992 Ship Production Symposium by Lovdahl, Martin, et al. (3).

The NIDDESC application protocols cover the following technical disciplines: structure, piping, HVAC, electrical and cableways, and outfit/furnishing items. Each discipline’s protocol is intended to cover all phases of a ship’s product model definition, starting with the contract design phase through to detail design and life cycle support of the ships in service.

In addition to defining the information content of a digital product model, each NIDDESC protocol lays out the logical interrelationships between the various types of information or digital data. These interrelationships are defined in terms of information models, called NIAM (Nijssen Information Analysis Method) diagrams.

These diagrams have proven to be of great value in the development of the DDG51 engineering product model since they can be used to establish the architecture of a relational database forming one of the cornerstones of the EPM.

The draft NIDDESC standards are being submitted to the International Standards Organization for approval as part of the STEP international standard. The work reported herein shows the usefulness of the application protocols in their present draft format, and demonstrates a frost-time implementation of the protocols for use in design efforts for the next flight of DDG51 Class ships. The challenge was to put together a working digital product model in a short time frame. The product model not only had to be rigorous in its adherence to the NIDDESC protocols, but also had to integrate the engineering aspects of the overall design process. Engineering processes have not previously been given great emphasis in CAD design work.

Gibbs & Cox, Inc. was tasked by the AEGIS program manager (PMS400D) to use the draft NIDDESC standards and the established DDG51 CAD model content standard as components in the development of an EPM to be used in the design process for DDG51 Flight IIA ships. The purposes of the EPM were to progress well beyond the project's previous goals for CAD; i.e., to integrate engineering analysis functions, and to create a totally digital design process for Flight IIA ships.

PMS400D'S direction was to extend CAD techniques into the early-stage design studies and pre-detail design process for future DDG51 Class upgrade/variant designs. Rather than performing design tasks in a conventional manner, it was decided to capitalize on the immense amount of detail design data available in the various 3-D CAD models already developed. Computer-aided engineering (CAE) applications were to be linked to these detail design databases. PMS400D directed concentration in the area of early-stage engineering. However, it was recognized from the start that the basic product model technology could later be extended to subsequent stages of the ship design and support cycle.

APPROACH

The initial task was to develop a workable product model definition for the DDG51 Class based on the NIDDESC standards, and on the goals set by PMS400D. The product model was defined to consist of two parts: a CAD graphics model developed for the ship construction program for Flight I ships and a non-graphics relational database containing all necessary data not in the graphics models. Initially, the product model developers concentrated on piping systems since that NIDDESC protocol (4) was the most fully developed. Later model development efforts included disciplines such as HVAC, electrical, and outfit/furnishings. The resulting product model was designed to support early-stage DDG51 flight upgrade design development, to be transportable to other organizations (both government and commercial), and to be contractor independent.

One of the first steps in this task was classifying the specified information content in each NIDDESC protocol as graphic or non-graphic data. The detailed approach for this step follows:

A. Each protocol was reviewed in detail to help distinguish between non-graphic elements (i. e, information not immediately available from or derivable from the CAD models), and graphic data.

B. The minimum set of data necessary to conduct engineering/feasibility studies for various types of ship systems was defined. It was intended, for example, that the information content in the combined graphic/non-graphic databases for piping systems would meet the requirements of the following tables in the NIDDESC piping protocol (4):

3.3.1.1 Equipment arrangement
3.3.1.2 Flow analysis
3.3.1.3 Piping system test definition
3.3.1.4 Connectivity check
3.3.1.5 Graphic presentation
3.3.2.1 Interference analysis
3.3.2.2 Connectivity check
3.3.2.3 Bills of material
3.3.2.5 Graphic presentation
3.3.3.2 Pipe installation /assembly definition
3.3.4.1 Support product model cross reference to external product support data/documentation
3.3.5.1 Configuration status and change tracking

c. A relational database was then established to contain all required non-graphic data. Tables for the various types of ship components and systems were created.

D. SQL (Structured Query Language) queries of the relational database were developed to extract all necessary support data.

Examples of graphic information include equipment dimensions, component orientations/locations within the ship, connectivity of components in a system, and piping system sizes (outside diameters). All of these types of data are contained in the DDG51 CAD models, or are easily derivable.

Non-graphic or engineering information selected for storage in the relational database system includes the weight of equipment items, component electric loads and load factors, and piping system component pressure drop coefficients. This information was keyed to the intelligence (stock numbers) in the graphics models. The relational database was designed using a relational database management system (RDMS) running on a RISC computer. It was intended that the combined graphic and non-graphic databases would in essence implement the NIDDESC application protocols' standards for information content.

A schematic representation of the engineering product model is shown in Figure 2. This figure illustrates the principle of combining graphics and non-graphics data to form the overall product model.

The design of the relational database portion of the EPM was guided to a large extent by the NIAM diagrams in the NIDDESC protocols. The diagrams, for example, show the interrelationship between piping system component pressure drop information, specifically, pipe inner diameter and roughness coefficient, and pipe component identification. The inter-relationships are easily converted to the

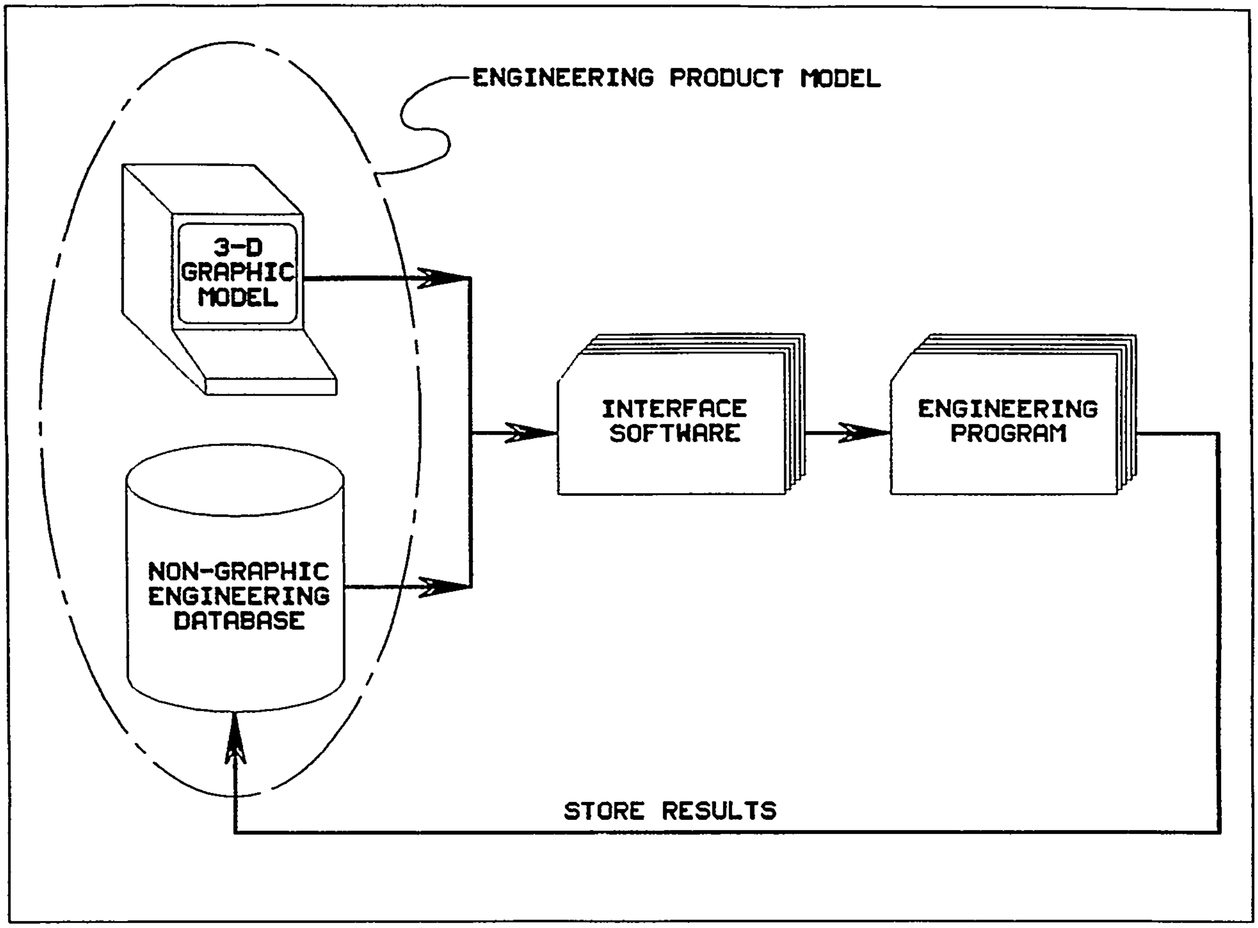

FIGURE 2. Engineering product model schematic.

primary/foreign keys associated with a relational database. Table I shows a portion of a relational database table that relates piping stock number, inner diameter, and relative roughness coefficient.

The process of converting the NIAM diagrams into database tables revealed certain instances in which the diagrams' logic was faulty. These problems were relayed to the authors of the NIDDESC protocols and, in most cases, were corrected in later versions of the protocols.

ENGINEERING PRODUCT MODEL

Once the basic graphic and non-graphic portions of the engineering product model were in place, it was necessary to link them for efficient interaction with each other and with existing engineering analysis software packages. Modern networking capabilities were used to link the graphics workstations to a computer which hosted both the relational database and the engineering analysis programs. Figure 3 illustrates the network established to run the EPM. This novel use of modern networking capabilities makes use of the EPM simple and rapid. It multiplies the computing power available to conventional CAD workstation users and allows true integration of design and engineering functions.

Engineering analysis packages already existed in each technical discipline. All that was required to complete the EPM was to write straightforward interface programs to extract the necessary data from the graphic and non-graphic portions of the EPM, and produce standard input data records for the engineering programs.

The list of disciplines for which interface programs have been written include the following:

- Piping pressure drop
- HVAC pressure drop
- System weights

Spef Pipe Item Spiv	Spef Pipe Item Internal Diam	Spec Pipe Item Rel Roughness
10031-001	0.410	0.000146
10031-010	0.545	0.000110
10031-028	0.710	0.000085
10031-036	0.920	0.000065
10031-044	1.185	0.000051
10031-052	1.530	0.000039
10031-061	1.770	0.000034
10031-079	2.245	0.000027
10031-087	2.745	0.000022

TABLE I. Typical relational database table.

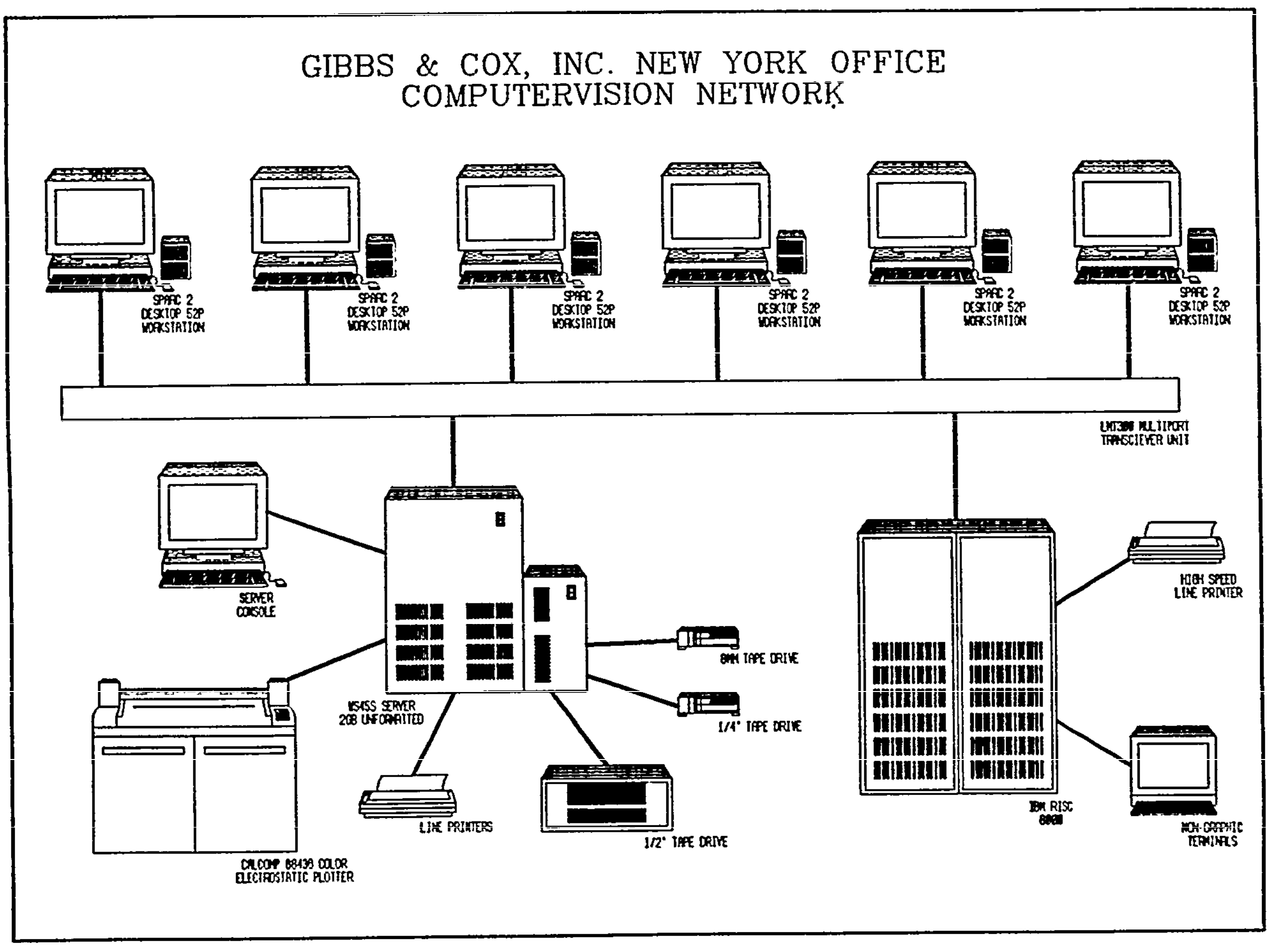

FIGURE 3. EPM computer network.

- Electric load analysis
- Heating/cooling load analysis
- Foundation design/analysis
- Voltage drop calculations, and
- Scoping of proposed changes

The traditional approach to performing engineering calculations on shipboard distributive systems has been to have engineers initially size the systems based on assumptions concerning the anticipated system routing. Experienced designers then actually do the detail design routing of the systems and manually check for mutual interferences between systems. After elimination of all known interferences, the distributive system drawings are prepared and issued. The original system engineers take the issued drawings and prepare final calculations based on the system drawing configuration. Often, the final calculations show a need to resize portions of a system and the engineering/design cycle must be repeated.

The traditional ship design and engineering process is a series of operations done over a relatively long period of time. The process also requires the passing of large amounts of information back and forth between various groups in an organization.

The EPM approach, in contrast, can greatly shorten the design/engineering cycles' duration and reduce the man-hour expenditures. Once a CAD graphics model of a distributive system is available---either as a first-cut crude model or as a final detailed model---the engineering product model's relational database and associated engineering programs can be used to do all the required system calculations. Since both the design and engineering groups are using a common CAD database as their basic frame of reference, the problems of communication between groups are vastly simplified.

The engineering product model has another significant effect which was not evident at the outset of the project. The EPM greatly simplifies configuration control of the resulting design and its associated engineering analyses. Because the design/engineering cycle times are shortened, engineering analyses can more easily be kept up to date. Using a common graphic database also means fewer opportunities for omissions or errors in the engineering calculations. Configuration control of the database is not onerous, since most of the information is catalog-related, and therefore changes relatively infrequently.

The EPM methodology can be applied throughout all phases of a ship design project. In the earliest phase, functional design, relatively simple first-cut graphics models can be developed as baselines. For DDG51 Flight IIA, a series of such simplified models have been assembled into a single enhanced geometry control model. For later design phases, detailed zone-level CAD models will replace the first-cut models. In all design phases, the combination of CAD graphics information with the EPM's relational database remains the principle for producing all required engineering calculations.

SUMMARY

The development of the DDG51 engineering product model has demonstrated the basic validity of the draft STEP standards issued by the NIDDESC Committee. Moreover, by subdividing data into classifications of graphic/non-graphic information, the engineering product model has shown one way in which NIDDESC protocols can be implemented in the near-term on existing CAD systems. using existing relational database software and modern networking capabilities makes it feasible to construct a ship product model

that conforms to NIDDESC standards now, without awaiting the creation of specific STEP standard software and/or translators.

Joining engineering calculation procedures with CAD graphics models significantly reduces engineering man-hours and shortens overall design/engineering cycles. For example, using the engineering product model methodology on a recent CAD zone model for DDG51 Flight II allowed calculations for an entire sprinkling system to be accomplished in four man-hours, and to be completed within one working day. Comparable calculations done by traditional methods would have required at least forty man-hours and several weeks, allowing time for passing data back and forth between the design and engineering groups. The efficiencies displayed in early testing of the EPM are impressive. The EPM should provide an answer to the Navy's pressing need in today's environment to reduce design costs for ships.

One final benefit of the engineering product model approach is a vastly simplified configuration control. Since both design and engineering groups use a common graphics baseline for their work, they will face fewer problems in the transfer of information between groups. The chances for error are obviously reduced, and the overall cycle time for every phase of the ship design process is shortened.

REFERENCES:

1. Joanne J. Ouillette, "DDG51 Class Computer Aided Design, " ASNE DDG51 Symposium, September 1992,
2. "DDG51 Class Lead Yard Services Digital Data Transfer Project Functional Specification, Revision C (phase II)," March 1990.
3. Richard H. Lovdahl, Jr., Douglas J. Martin, et. al., "The NIDDESC Ship Product Model: The STEP Solution, " SNAME 1992 Ship Production Symposium, September 1992,
4. Douglas J. Martin, "NIDDESC Piping Application Protocol, Version ().7, " March 1992.

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Composites for Large Ships

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ABSTRACT

Composites, frequently referred to as fiberglass or FRP, are usually thought of as the material of choice for recreational boats. Recently though, composites have been used for 57.3 m (188 ft) minehunters and a 49 m (161 ft) yacht. Ten years ago these FRP vessels would have been at the upper limits of perceived size limitations, but practical limitations on the size of vessels using composites as the primary structural material are premature due to continuing advances in the materials and processing technology.

Composites are used for small sections of large steel vessels including non-pressure hull decking for submarines, weapons enclosures for destroyers, and funnels on cruise ships. Potential uses on large cargo vessels include bulbous bows, hatch covers, stern fairings, deck machinery enclosures and non-structural interiors. This paper reviews current usage and explores future potential on the use of composites on larger vessels.

INTRODUCTION

Generic composites are two or more distinctly different materials combined into (but not dissolved into) one structure to perform a function neither material is capable of doing singly. Steel reinforced concrete is an example where the steel carries the tensile loads and the concrete mainly compressive loads. Ferro-cement yachts, power boats and barges have been built in limited numbers with limited success, because of difficult construction, weight and sweating problems. Metal matrix composites use small amounts of very high strength fibers, such as boron, in a metal matrix, such as steel or aluminum. However, due to weight or expense, these composite types are not common to bulk applications found in marine use.

Some of the many advantages of Fiber Reinforced Plastic (FRP) are its light weight, high specific strength, ease of forming, resistance to corrosion, and long life. Some specific disadvantages are flammability, relatively low modulus, and the generation of volatile organic compounds during lamination. These factors are discussed in another section, but the advantages and disadvantages of composites have been covered by many other sources and need not be belabored here.

For common marine industry use, composites are generally a glass, Kevlar® or carbon fiber in a thermoset plastic polymer matrix. FRP is the common referring acronym. Glass Reinforced Plastic (GRP) was a frequently used term in the past, but is now out of date because of the more common use of Kevlar® and carbon. "Fiberglass" or just “glass,” Reinforced Plastics (RP), and Polymer Matrix Composites (PMC) are terms still used to refer to the same group of materials. With many different types and fabric weave arrangements for the common fibers, many formulations of the basic resin types, and vastly different properties achieved from various fabrication methods, marine composites comprise an almost infinite choice of materials.

Marine composites have been used for limited applications on large steel ships, mainly on combatant types. FRP is used on submarines for flooded nose fairings, diving planes and non-pressure hull decks. A weapons enclosure prototype (1) has been developed for use on a destroyer. The OSPREY class coastal minehunters (MHCs) have their primary structure in FRP. The wood mine countermeasure vessels have numerous FRP extrusions for rails, ladders and other minor attachments, and their entire funnels are made of FRP.

Because of a U.S. regulatory requirement for steel or equivalent structure for carrying more than 149 passengers, the use of composites on commercial passenger vessels

has been limited to small passenger vessels (less than 100 gross tons) and escape craft for larger passenger vessels. The passenger load allowed on U.S. Coast Guard certified FRP small passenger vessels can be easily carried on a 27 m (87 ft) FRP monohull. Larger FRP vessels are in service and could handle more passengers. Most of these are yachts, but the MHCs and Norwegian 450 passenger surface effect ships (SESs) demonstrate that larger FRP vessels are practical.

FRP hatch covers are used on dry cargo barges for inland transportation but are not used on ocean-going vessels. Pre-formed FRP deck gratings are used on raised catwalks on oil tankers. However, there is no extensive use of composites on ocean-going commercial vessels. Criteria for considering composites on large steel vessels in various applications are reassessed by this paper. Limiting issues of damage tolerance, bonding and mechanical attachment strength, flammability, classification and regulation are discussed.

BASIC MATERIALS

The most commonly used composites in the marine industry are glass fibers, Kevlar® or carbon fiber in a thermoset plastic polymer matrix, generically referred to as FRP. Table I shows the raw fiber properties of some of these materials (1). However, after the materials are woven or stitched into a fabric and combined with resin, the actual properties of the finished laminate varies drastically and is quite dependent on the method of fabrication. Table II is a comparison of some of the basic properties for an 800 gm/m^2 (24 oz/yd^2) E-glass laminate of either woven roving (WR) or unidirectional (UNI) weave with different fabrication methods and different resins (1, 2).

Fiber	Tensile Strength psi X 10^3	Tensile Modulus psi X 10^3	Ultimate Elongation	Cost U.S.$/LB
E-glass	500	10.5	4.8%	0.80-1.20
S-glass	665	12.6	5.7%	4
Kevlar®	525	18	2.9%	16
Spectra® 900	375	17	3.5%	22
Carbon	350-700	33-57	0.38-2.0%	17-450

Table I Raw Fiber Properties

One would expect the unidirectional polyester resin laminate to be much stronger than the WR polyester laminate, but the glass content referenced (2) was “approximate” and the possible differences in structural qualities of different grades of polyester resins can be significant. However, the superiority of a vinyl ester resin laminate with 70 percent glass content is obvious. Conversely, poorly done (high resin content) laminates can have very poor physical properties.

Differences in the test methods can also produce physical property data that is not directly comparable. For example, when a simple tensile test is performed on a unidirectional laminate, the allowed variability in the sample size can cause significant differences in the test results. If the sample size is 25 mm (1 in) wide and 150 mm (6 in) long, and is cut 5 degrees off the axis of the fiber direction, half of the supposedly continuous fibers are cut off. A 150 mm (6 in) wide by 300 mm (12 in) sample cut with the same 5 degree error would only have 8.7 per cent of its fibers cut. Standardizing the standard test methods is a project of great interest to the FRP industry, the Coast Guard, the American Bureau of Shipping (ABS) and the Navy, and is being addressed by the Society of Naval Architects and Marine Engineer’s (SNAME) Panel HS-9, Hull Structural Materials.

PROPERTY	WET LAYUP 50% POLY WR	WET LAYUP 50% POLY UNI	SCRIMP 70% POLY WR	SCRIMP 70% V.E. WR
TENSILE STRENGTH **(ksi)**	**46.8**	**35**	**67.3**	**70.9**
TENSILE MODULUS (msi)	**3.2**	**2.2**	**4.5**	**4.6**
COMPRESSIVE STRENGTH (ksi)	39.1	37	42.1	68.6
FLEXURAL STRENGTH (ksi)	52.2	65	66.8	90.0
INTERLAMINAR SHEAR STRENGTH (ksi)	3.3	NA	4.5	7.3

50% or 70%=% glass content by weight, POLY = polyester resin, V.E. = vinyl ester resin
SCRIMP™ = Seemann Composites Resin Infusion Molding Process

Table II Laminate Properties

EXISTING COMPOSITES APPLICATIONS

The widespread use of composites, mostly FRP, in various parts of the marine industry is still not well known or understood in the world of large steel ships. The difficulties encountered with the Navy's "Integrated Technology Deckhouse Project" **(3)** demonstrate this. Some of those difficulties were a reluctance to deal with any processing of the panels, mechanical and adhesive fastening of the FRP-steel joints, and attachment of outfitting items. However, current applications of marine type composites (as opposed to high technology high cost aerospace composites) in Navy and commercial projects seem to indicate a change in thinking, and serve to justify the further application on commercial vessels.

Most notable of large scale FRP applications is in the OSPREY class MHCs being built by both Intermarine and Avondale. These vessels are 57.3 m (188 ft) long, and are built of a specially developed spun woven roving laminated with impregnators into a sectional steel mold. They are heavily constructed monocoque structures with a 76 mm (3 in) thick single skin laminate (200 mm (8 in) at the keel) to take severe underwater blasts, and are naturally anti-magnetic. Although the specialized nature of the MHCs is not likely to support a direct transfer of composites technology to commercial vessels, their existence indicates what can be done.

In July of this year the 49 m (161 ft) sandwich composite yacht EVIVVA was launched by Admiral Marine in Port Townsend, Washington. This vessel is significant in that it is the largest non-military sandwich composite vessel yet built; it embodies the best qualities of composites in that it is light weight and structurally robust. Cores used in its sandwich structure consist of

- damage tolerant linear PVC foam bottom and side shell,
- high density acrylic co-polymer foam for the keel and engine girders, and
- cross-linked PVC foam for decks and deckhouse.

Because of the yacht quality finish, extensive use of honeycomb for light weight joiner work and interior cabinetry (4), and three year build time, this yacht is not likely to directly justify use of FRP for similarly sized commercial vessels. However, it shows that an FRP vessel of this size is feasible. This vessel was constructed using relatively low cost wood one-off female molds. It would have placed 91st in last year's listing of the 100 largest yachts (5); only one other yacht was FRP, four were aluminum, and the rest were steel.

Of more immediate interest for commercial shipbuilding are the efforts of

Italian shipbuilder Fincantieri, which is actively using composites in shipbuilding (6). They are focusing mainly on weight reduction and stability effects, but they are also trying to minimize the use of light alloy, reduce cost, cut maintenance and improve aesthetics. They have used FRP for funnels on two large classes of cruise liners, for various piping applications, and they are doing research in collaboration with classification societies to use more composites in deckhouses.

One of the Fincantieri FRP funnel installations is a triple stack design for two cruise ships in the Costa Crociere Line. Each funnel is an elliptical FRP sandwich structure 3 mx5mx12m (10x16x40 ft) and was designed to withstand a 100 knot wind and inertial loads. Savings were on the order of 50 per cent for weight and 20 per cent on cost compared to the aluminum and stainless steel structures they replaced. In addition, the appearance of the FRP funnels is more to the owner's satisfaction.

Another of their stack designs is on three Holland America Line cruise ships. This is a large single stack design with FRP panels attached to a steel frame. The owner's logo is molded into the side panels. The logo molds are also used for creating decorative FRP panels which are fitted to other parts.

Use of FRP pipe for non-critical applications on all classes of commercial vessels is relatively commonplace, but still requires mention here. As early as 1976 (7) the NSRP evaluated use of FRP pipe and reported savings of 15 to 20 per cent in cost; because at that time FRP pipe was more expensive than steel, the savings was mostly related to installation labor, ease of handling due to the lighter weight, and ease of joining due to adhesive bonded joints. However, life cycle cost gains were expected in the areas of corrosion and pumping efficiency. Problems were encountered in making custom bends, valve support and hanger design. Current application experience has eliminated most of these problems.

Crucial to the widespread application of composites in U.S. commercial and auxiliary vessel construction will be the U.S. Navy's treatment of composites, and the confidence that the Navy builds with shipbuilders in using FRP. Four application areas demonstrate that the Navy is advancing its use of composites:

- continuing work on deckhouse projects,
- the Mark V patrol boat
- projects on the R&D submarine, and
- the new standard landing craft program.

The various composite deckhouse programs (3, 8) are being conducted to support replacement of aluminum deckhouses in surface combatants due to cost, fabrication and fire problems that are associated with aluminum. This seems unusual, since one of the major problems with composites is their behavior in fire and elevated temperature environments. Composites have a relatively low heat distortion temperature, burn, and give off toxic gases. However, composites do not readily transmit heat, can easily be coated to enhance their fire resistance, and exhibit better overall structural integrity than similar structures of aluminum. The advantages still outweigh the disadvantages, and FRP remains a viable alternative as research continues.

In the Navy's Mark V patrol boat procurement, one FRP and two aluminum prototypes will be built and evaluated in early 1994. The Equitable yard of Trinity Marine, with U.S. Marine building the sandwich hulls, will build the FRP vessel which is a 25 m (82 ft) monohull capable of 50 knots. This is the Navy's largest FRP performance craft (besides the "stealth" SEA SHADOW) to date.

The use of composites in the U.S. Navy's research and development (R&D) submarine, the USS MEMPHIS, demonstrates the extent of forward thinking involved in the program (9). At that time (two years ago), the following items were scheduled for implementation and are believed to have been executed

- main propulsion shafting,
- various machinery foundations,
- air flasks,
- control surfaces,
- sail, and
- the stem structure.

Future candidates in the same program include:

- ballast tanks,
- piping and ducting,
- machinery
- storage tanks,
- decks and hatches, and
- hydrodynamic fairings.

Solid single skin laminates are already in fleet *use* for the nose sections on submarines.

The Germans are already using sandwich composite, non-pressure hull, deck structures on their subs. The structural foam in the sandwich is a high density (400 kg/m3 [24 lb/ft3]) acrylic co-polymer foam that is also used in parts of deep diving submersibles. With submarines being weight sensitive, and with the amount of distortion, fairing and noise isolation that is involved with current thin plate high strength steel construction of these deck structures, this application area should yield very favorable results on U.S. subs.

The Advanced Material Transporter (AMT) is being developed by the U.S. Navy, partly as a replacement for aging utility landing craft (LCU), but more to be complimentary to the air cushion landing craft (LCAC) (2). It is designed to carry 81 t (90 short tons) of cargo at 20 knots in sea state 3 on a 34 m (111.7 ft) hull. Its basic design is a solid FRP bottom and side shell with a balsa cored deck and deckhouse. A one third scaIe validation model has been constructed using the Seemann Composites Resin Infusion Molding Process (SCRIMP™) method, which the Navy calls the Vacuum Assisted Resin Transfer Molding (VARTM) process. The process yields the very high physical properties shown in Table II without the need for matched molds, a requirement for most RTM processes. The developers of this craft have stated that it was difficult to convince the littoral warfare people in the Navy and Marine Corps to accept a composite craft, but the fact that this program is proceeding is an indication that composites have an improved image in the minds of military decision makers.

Additional developments in naval applications of composites (9) include:

- weapons enclosures,
- gun enclosures,
- rudders,
- dry deck shelters,
- missile blast shields,
- ladders,
- deck drains,
- rails,
- radomes,
- hatches,
- masts, and
- stacks.

LARGE COMMERCIAL SHIP APPLICATIONS

An old but still relevant report by the Ship Structures Committee (SSC) (10) investigated the possibility of constructing a 143 m (470 ft) cargo vessel of FRP. Most of the design exercise was done as a direct conversion of the existing steel vessel.

The FRP vessel that resulted from this study was not optimized to increase the moment of inertia of the midships section, so using a material tensile modulus (the compressive modulus is nearly the same) of only 2×10^4 MPa (2.9×10^6 psi), deflections of the hull girder were five times that of the steel structure. The report theorized that a deflection of two times that of steel would have been acceptable. However, with use of available modem materials and fabrication methods, this deflection limit could be met. With increased use of unidirectional material applied by the SCRIM™ or a high efficiency impregnator (11), a 3.8×10^4 MPa (5.5×10^6 psi) tensile modulus is possible. If the midships section is optimized for maximum moment of inertia, by reducing hatch size or increasing the depth 10 per cent, the result is a bending stiffness half that of the steel vessel.

A number of other limitations listed in the SSC report have been overcome by materials presently available. Table III compares these former limitations to current solutions.

One point made by the SSC report was that cored laminates were not feasible due to high cost of purchase and installation. It correctly stated that balsa cored laminates should not be used in the hull, however, these laminates are very inexpensive compared to equivalent single skin laminates, and quite applicable to interior structure, especially for fire resistant divisions. Polyvinyl chloride foams are nearly two to three times as expensive as balsa, but they could be used in a number of applications that would make a large FRP vessel significantly lighter and less expensive to construct. The SSC report predicted that the use of a sandwich laminate would not be an advantage in the middle portions of the ship due to the need for a large cross sectional area of continuous FRP to keep the midships section stiff. However, use of a sandwich laminate outside the middle 40 per cent of the length is feasible.

LIMITATION	OLD ARGUMENT	CURRENT SOLUTION
HULL STIFFNESS	Only 20% of steel	Increase I, better fabrication, unidirectional fabrics
ABRASION	Low resistance relative to cargo handling, bottom scraping	Kevlar® felt
FUEL TANKS	Laminate flaws allowed fuel to seep into the structure in integral tanks	Use of two layers of mat and a veil with V.E. resin adequate for sealing integral tanks
LAYUP	Hand layup inadequate, impregnators not developed	Impregnators well developed, SCRIMP™ or equivalent under development
SECONDARY BONDS	Weakest part of technology	Well developed guidelines now in place, can be made strong
FIRE RESISTANCE	Resins subject to fire, fire retardant (FR) resins expensive and weak	Modern FR resins much better and reasonably priced, FR coatings available

Table III Perceived limitations of FRP in ships.

The SSC report also identified highly shaped bow and stern sections as being feasible based on cost and weight, regardless of whether the ship behind these sections are steel or FRP. Large bulbous bows are very difficult to shape in steel and even harder to fabricate by welding, especially the inside structure. The cost advantage of FRP bows over steel is greater than that reported if the following construction scheme (prescribed by Johannsen 20 years ago [12]) is followed.

1. Construct a wooden male batten frame 25 mm (1 in) inside the desired molded line, arranged with a 12 to 1 scarfed joint.
2. Cover with a damage tolerant linear PVC foam, heat formed to achieve extreme curvatures, attached from the inside by wood screws.
3. Laminate an 8 mm (0.31 in) FRP outer skin.
4. Back out screws to detach foam from frame, lay part in cradle.
5. Bond in second layer of 25 mm (1 in) foam and laminate an 8 mm (0.31 in) FRP inner skin.
6. Repeat the process for the mirror image opposite side.
7. Bond the two halves together.
8. Laminate the joints, fair, and gelcoat.

Admittedly, this is a simplified scenario, but it has been used for a number of other projects ranging from custom boats to large decorative architectural works. The same procedure could be used for the whole bow or stern section to eliminate some of hardest to form and weld curved panels in shipbuilding.

The flammability issue is one that has always plagued FRP construction in general and marine use in particular, especially in terms of passenger vessels. However, the Coast Guard has been considering the use of composites on small passenger vessels for five years and has recently given tentative concept approval for a vessel with a large amount of the structure made of FRP. The Coast Guard has also been doing research on fire retardant coatings applied to FRP.

Although there are many other issues to be considered in the use of composites in large ships, one last issue that frequently surfaces is attaching FRP to steel. This was addressed in the Navy's deckhouse projects by using a combination of bonding and bolting (3). Although the bond strength of an aggressive

vinyl ester resin to steel is on the order of 9650 Pa (1400 psi) (13), further Navy research has shown that bonding alone is not adequate to resist nuclear air blasts and combination joints are required. In more normal applications, bonding has proven adequate to completely cover the underwater hull of an aging steel hull with a new sandwich composite shell (14). Therefore, attachments of FRP to steel or alumininum should not be considered a barrier to using FRP with metals in marine construction.

The Coast Guard, the American Bureau of Shipping (ABS), and other regulatory agencies and classification societies are steadily improving their rules and positions relative to composites, and are open to new ideas.

CONCLUSIONS

Arguments for and against the use of composites in various marine applications have been advanced before. Generally, as the age of the argument grows, its validity wanes. Marine type composites have been applied to advanced projects ranging from large and very expensive yachts, to highly loaded utilitarian landing craft, to submarine nose cones. Common use of composites for commercial vessels is feasible and should be pursued.

REFERENCES

Greene, Eric, "Marine Composites," Ship Structures Committee Report **SSC-360,** June 1990.

2. Nguyen, Loc B. J. C. Kuo, M. O. Critchfield and J. D. Offutt, "Design and Fabrication of a High-Quality GRP Advanced Material Transporter," ASNE Small Boats Symposium, May 26-27, 1993.

3. Cahill, Pat, "Composite Materials and Naval Surface Combatants: The Integrated Technology Deckhouse Project," *Journal of Ship Production,* Vol. **8, No.** 1, February,

4. "Of Material Interest," *Advanced Materials & Processes,* Vol. 142, No. 1, July,

5. O'Boyle, Bonnie J., "The Worlds Largest 100," *Power and Motoryacht,* Vol. 8, No. *8,* August, 1992.

6. Maccari, A. and F. Farolfi, "Innovations and Technical-Economic Aspects of Structural and Non-Structural Applications of Composite Materials on Large Passenger Vessels and Merchant Ships," Conference on Nautical Construction with Composite Materials, Paris, December 7-9, 1992.

7. Uberti, G. A. and Ken Evans, "Fiberglass Reinforced Piping for Shipboard Systems," NSRP Report 0060, Todd Shipyards Corporation, July 1976.

8. Greene, Eric, "Fire Performance of Composite Materials for Naval Applications," Structural Composites, Inc. contract report, May, 1993.

9. "Use of Composites in Load Bearing Marine Structures," September 25-26, 1990 National Conference Reports, Vol. I & II, Ship Structure Committee, National Academy Press, 1991.

10. Scott, Robert J. and John H. Sommella, "Feasibility Study of Glass Reinforced Plastic Cargo Ship," Ship Structures Committee Report SSC -224, 1971.

11. Raymer, John F., "Large Scale Processing Machinery for Fabrication of Composite Hulls and Superstructures," *Journal of Ship Production,* Vol. 7, No. 4, November, 1991.

12. Johannsen, Thomas J., "One-Off Airex Fiberglass Construction," Buffalo, NY: Chemacryl, Inc., 1973.

13. "Derakane Resins," Dow Plastics, Technical Product Information, January 1989.

14. Horsmon, A. W. Jr., "Permanent Composite Cladding of Deteriorating Steel Hulls," *Journal of Ship Production,* May, **1992.**

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A Plan for Identifying A More Producible Structure for Tankers

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ABSTRACT

This paper addresses a plan for research and development leading to alternative structural system concepts for tankers. These should decrease labor requirements in design, fabrication and outfitting phases. The plan begins with addressing those aspects of concurrent engineering which, when applied, will result in the optimum characteristics with least cost from both the builders' and owners' perspectives. The next steps address identifying characteristics of structural systems which offer promise, and the assembly of these into alternative structural system concepts based on their apparent potential for improved producibility. Then, the application of the systems to specific vessels and methods to evaluate the improved producibility are considered.

INTRODUCTION

Overview

It is generally acknowledged that the cost of acquiring ships from U.S. shipyards is higher than from foreign shipyards, particularly from the Far East, Southern Europe and Brazil. The reasons have been vigorously debated; government subsidy and availability of favorable financing in these overseas locations have been identified as very serous potential reasons for the differences. These are generally not within the control of the shipbuilding community. However, it has also been acknowledged that there are other significant differences of a more technical nature which will have a substantial impact including: labor hour requirements for design and construction; materials, equipment, and machinery costs; shipbuilding practices and facilities; long lead delivery times; stringency of standards; contractual processes; and institutional constraints.

During the last twenty years the shipyards, various agencies of the government and the Society of Naval Architects and Marine Engineers (SNAME) have tried to address the matter and improve producibility. The U.S. shipyards have acknowledged the advancement of Japanese shipbuilding techniques, and, along with the U.S. Maritime Administration (MARAD), they have imported technology from innovators like IHI, who has transferred information to Bath Iron Works, Newport News Shipbuilding, Ingalls Shipbuilding, Avondale Shipyards, and others. MARAD and later SNAME have sponsored the National Shipbuilding Research Program (NSRP), which supports extensive and varied research in shipbuilding technology from design through delivery. Yet, a significant gap still appears to be present between the U.S. and major world shipbuilders. Are the reasons a lack of innovation, sufficient effort, facilities enhancement or application?

The time required for the construction of a vessel has been identified as having a major impact on vessel cost. Reported delivery times in foreign shipyards are considerably less than U. S. shipyards. The reasons for this must be largely tied to the nature of the structure being manufactured, and to the degree it facilitates fabrication and installation of outfit prior to erection on the building docks. The design phase and its integration with construction has a significant influence on achieving this goal. The purpose of this plan is to aim at the heart of those matters which can make a difference and are in the shipbuilder's control.

The outline of the plan presented herein was developed in the course of preparing a proposal in response to the U. S. Coast Guard (USCG) Ship Structure Committee solicitation for "Hull Structural Concepts for Improved Producibility (SR-1351), " which has subsequently been awarded to M. Rosenblatt & Son, Inc.

Background

Although the recent upturn in international shipbuilding has currently stalled, it is acknowledged that the world's aging tanker fleet must be replaced in the years to come. This will provide a magnificent opportunity to revitalize shipbuilding in the U.S. Furthermore, the passage of the Oil Pollution Act of 1990 (OPA '90) in the U.S. has resulted in new tanker arrangements to be provided, specifically double hulls,

and this allows significant latitude for the development of designs with innovative enhancement for producibility. These could give the developer a significant advantage over the competition.

The time is right for the U.S. shipbuilding industry to address this potentially crucial crossroad. An approach may be to "develop alternative structural system concepts" for potentially desirable tanker sizes, 40,000 and 100,000 DWT. These should result in decreased labor requirements in the design, construction, and outfitting phases of a shipbuilding program, as well as provide for low cost maintenance during the life of the vessels. Addressing these types and sizes of vessels will provide information to shipbuilders for use in the upcoming boom for rebuilding the world fleet.

Decreased labor requirements will obviously lead to reductions in the time and cost of building ships. By introducing superior alternative structural systems into the construction program, possibly together with other innovative technologies, significant improvements will be obtained in the fabrication, assembly and erection time schedules. As a result, an environment will be created for the U.S. shipyards to favorably compete with European and Far Eastern shipyards for world ship construction orders.

It is noted that the NSRP, more recently under SNAME sponsorship and U.S. Navy funding, has long dedicated its efforts to investigate methods of improving producibility in shipbuilding. Some of the projects that are currently included in the NSRP'S scope are closely related to this matter, e.g., Project 4-93-6, which calls for the development of a design manual for producibility of hull foundations, and 4-93-2, which is directed at reducing ship construction time and cost in U.S. shipyards. Other NSRP projects are also circumstantially related to the subject considered herein. It will be extremely important to summarize the massive NSRP research and development program and build upon it, rather than risk re-investigating some of the same matters.

Without a doubt, constraints may be imposed on the considerations due to the current nature of the existing shipyards and their facilities. Yet further involvement of U.S. shipyards in commercial shipbuilding must take place within the next few years; otherwise, it may be too late. Consequently, any alternative approach must not rely on massive facilities enhancements.

In all this, the shipowner must not be forgotten. New ships must be reliable and maintainable, or the shipowner, the customer, may not be willing to purchase a vessel. The automobile industry has established a precedent where a dissatisfied customer has turned to foreign sources for a major portion of the product.

Summary

The meeting of the objectives presented herein lie at the heart of the future of shipbuilding in the U.S. To be successful the plan must concentrate on the structural systems and their impact on design, fabrication, outfitting and maintenance. It should not dwell on policy, major facilities enhancement or futuristic scenarios.

The output should consist of one or more alternative primary and secondary structural system concepts for each ship which demonstrate the ability to achieve reduced labor hours for contract and detail design, construction and improved maintainability. The installation of ship's outfit, equipment and piping in subassemblies prior to erection on the ways of building docks must be incorporated in the strategies, as this has been shown to be a significant contribution to increased producibility.

The sections which follow address the principal components of the plan: use of concurrent engineering principles; identification of potentially advantageous structural elements and alternative systems; identification of the sample applications which should identify their merits; and evaluations of alternative system concepts needed for comparison purposes.

CONCURRENT ENGINEERING REQUIREMENTS

General

Concurrent engineering is an approach to developing a product which seeks to integrate design, production and user requirements from the outset, to arrive at the optimum solution in the most direct manner. The objective for the matter at hand should be the definition of those characteristics of concurrent engineering which, when applied to tanker structural design, will result in producing the optimum characteristics with least cost.

At a point in time when all possible alternative structural concepts will be considered to evaluate their pertinence, the level of design can only be conceptual/preliminary. A recent report discusses introducing the ship construction method and sequence earlier into the design process, with emphasis on preliminary build strategy, subdivision of the hull into erection units and modules, and advance planning for the development of work instruction packages during the detail design (l). The interests of the shipowner has been incorporated as well. By expanding on this

approach, a concurrent engineering philosophy and its characteristics for this project can readily be established.

Philosophy of Construction

The objective of both the shipyard and owner should be identical in the delivery of a ship. However, their concerns along the way will be different.

Shipowners are principally concerned with obtaining a vessel that will meet their performance requirements at a favorable price and schedule. They may tend to be unconcerned with the distinction between the design phases, but will seek to understand the nature of not only the principal design characteristics, but the intended detail of the construction and character of the equipment provided, in particular as to how it impacts reliability and maintainability. As an additional concern, OPA '90 has placed a significant amount of liability for spills on the shipowners, and it can be expected their concern for risk, reliability and safety will be especially acute.

Shipyards are concerned with the design and construction details of the vessel once a contract has been signed. Theoretically, a shipyard is free to incorporate the production attributes of the organization into the design process at any stage. As personnel most experienced in production may not always be associated with the design departments, successful integration of production into design must involve a coordination of disciplines, which does not always occur.

Design, construction and shipowner requirements should be properly integrated to achieve the most desirable structural alternatives at lowest cost.

STRUCTURAL ELEMENTS

G

The characteristics of the structural elements which can be utilized in assembling structural systems for double hull tankers should be identified first. These will include tanker structural concepts, individual structural components, structural standards, and processes. This can be achieved through the identification of structural elements utilized in the past, proposed concepts, variations suggested by new and relatively modest fabrication equipment, and characteristics suggested for possible reduction of potential oil pollution.

Overall Considerations

Tank vessels have been traditionally designed as single skinned hulls. Depending on the size of the vessel, longitudinal bulkheads are often present; and the overwhelming majority of single skinned designs are longitudinally framed (Figure 1). As a result of major oil spills and the resulting damage to the environment, the U.S. Congress has mandated in the OPA '90 the use of double skinned tanker designs (Figure 2) as an effective means to protect the ocean environment from potentially devastating oil pollution. Since then, a number of alternative generic configurations have emerged as well, most prominently, the mid-deck design (Figure 3), and are being considered by the international community, although not permitted by OPA '90. All of the new designs are aimed at achieving the same objective, i.e., to reduce the likelihood of oil spill and to reduce the amount of outflow in the event of hull puncture.

The function of a tank vessel's structural system may be viewed from the standpoints of normal operation and casualty operation. In providing adequate resistance for normal operations, the objective in structural design is to maintain structural integrity of the hull girder, of bulkheads, decks, plating, stiffeners and details. Other considerations relate to vessel size, complexity and heaviness of the structure, producibility, and maintainability. In terms of casualty operations, the objective is to maintain vessel integrity and to protect cargo, or, conversely, to protect the environment from oil pollution in case of a casualty. In this case, the primary considerations should encompass:

1. Resistance to fire and explosion damage and its containment;
2. Resistance to collision and grounding damage;
3. Containment of petroleum outflow if damage does occur; and
4. Maintenance of sufficient residual strength after damage in order to permit salvage and rescue operation, and to minimize further damage and spilling of oil.

Tanker structure is characterized by structural arrangements consisting of a number of elements oriented in repetitive patterns. Examples are the traditional transverse system consisting of transverse frames supported by girders and bulkheads, and the longitudinal system consisting of shell longitudinal

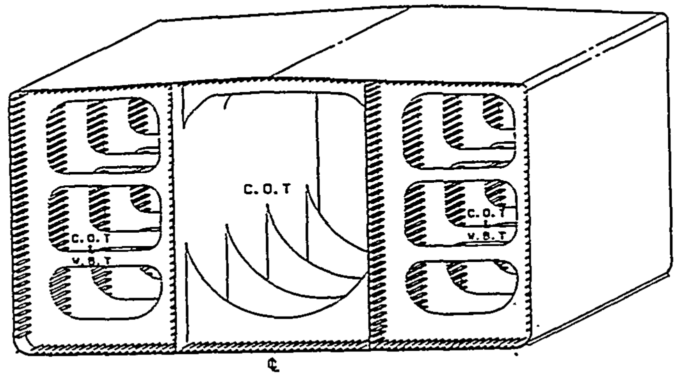


Figure 1: Single Skinned Tanker

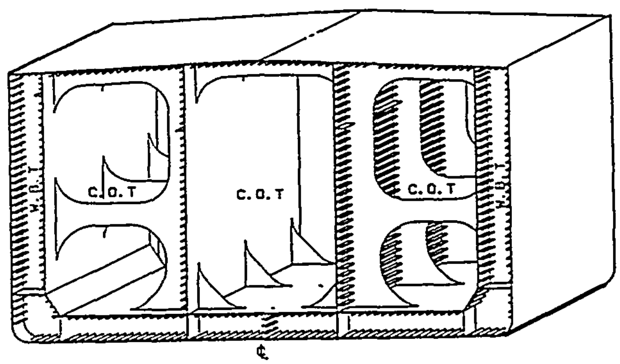


Figure 2: Double Hull Tanker

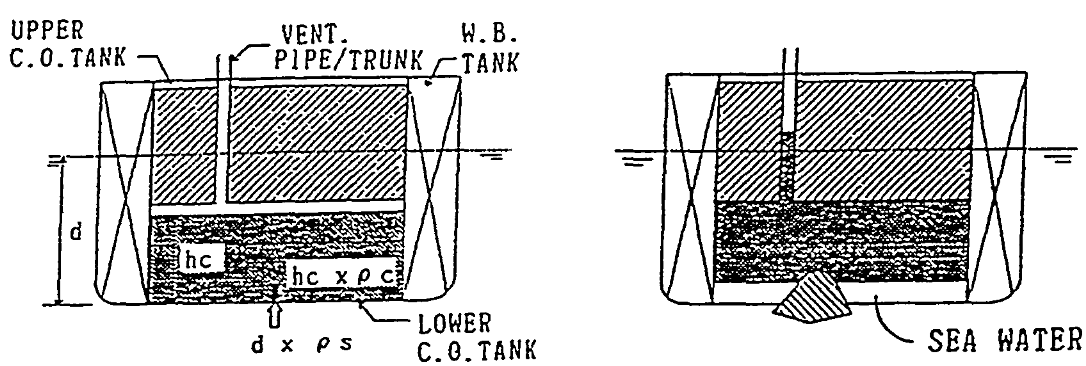


Figure 3: Mid-Deck Tanker

supported by web frames. These have been incorporated in most tanker construction to date.

In recent times unidirectional double hull structural systems have received attention from the commercial community (2). Specifically, this hull structural system uses a double hull structure supported between transverse bulkheads by a series of longitudinal girders between the hull skins (Figure 4). structural simplification is significant with intersections between the longitudinal and transverse members reduced to a minimum. Other new concepts have been developed as well, such as the dished shell plate system (3), wherein the added strength due to the curvature in shell and bulkhead plate supplants the need for stiffeners.

o Longitudinal girders
o Deck
o Transverse bulkheads
o Longitudinal bulkheads
o Material

Furthermore, and although not currently a specific or impending regulatory requirement, alternative structural systems can provide varying amounts of protection of oil outflow during collision. A theoretical estimate of energy absorption during collision and prior to cargo tank penetration is shown in Table I (4). The results indicate a wide range of energy absorption potential for the specific embedments considered.

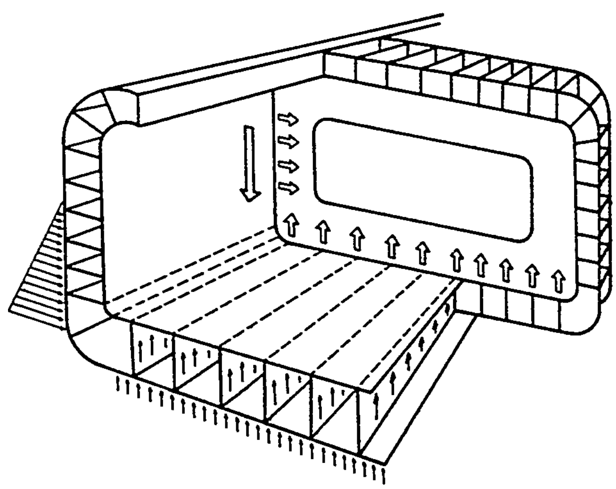


Figure 4: Load Transmission Mechanism (2)

As an example, the structural elements representative of conventional and unidirectional systems are as follows:

Conventional Single and Double Hulls

o Shell (inner and outer)
0 Side and bottom stiffeners
0 Web frames
0 Brackets
0 Deck
0 Transverse bulkheads
0 Longitudinal bulkheads
0 Transverse floors
0 Material

Unidirectional Double Hull

o Shell (inner and outer)

It is important, as well, to consider the philosophy behind and characteristics of the structure as significant production improvements may be possible. Hofmann et al (5) have shown that for the longitudinally framed T-AO 187 class fleet oiler the following producibility features result in savings:

o maximized areas of flat plate;
o maximized areas of single curvature, for remaining shell plating;
o increased frame spacing and reduced numbers of piece parts in structural assemblies;
o standardized brackets and web frames, and use of bilge brackets in lieu of longitudinal stringers in the bilge turn area and
o carefully arranged erection joints.

Vessel	Single Skin	Double Skin	Unidirectional	Single Skin
DWT	138,180	138,180	138,180	138,180
Depth m (ft)	19.4 (63.5)	19.4 (63.5)	19.4 (63.5)	21.0 (68.9)
Stiff Spcg m (ft)	0.91 (3.0)	0.91 (3.0)	0.91 (3.0)	Unknown
Web Spcg m (ft)	3.81 (12.5)	3.81 (12.5)	N/A	Unknown
Bhd Spcg m (ft)	15.24 (50.0)	15.24 (50.0)	15.24 (50.0)	Unknown
Energy/m Kjoules/m	15,700	28,400	60,090	18,360

Table I: Comparison of Sideshell Energy Absorption (Per Meter of Depth)

Structural Components (6):

A number of structural components can be identified which are new or have not found wide applications in the past but offer potential advantage. These are enumerated below:

Tapered Plating:

1. In 60's and 70's US Steel claimed the ability to produce tapered plates. Longitudinal tapering of plate has been accomplished in Germany and France (7).

2. If tapered plates were used for sheer and stringer stakes, for instance, weight, welding, and edge preparation could be reduced.

3. Fatigue cracking might be reduced because of smoothness of transition.

4. Ship resistance would be improved (slightly).

5. Notching in supporting structure would be eliminated.

6. The disadvantages are added cost, lack of standardized sizes (width, thickness, taper all vary), and material handling and storage are more complex. Repair in service may present difficulties.

Corrugated, Swedged, and Dished Plates:

1. Used to eliminate stiffeners.

2. Increases buckling resistance over flat plates.

3. Saves on welding and residual stresses.

4. Would have to be corrugated, swedged, and dished in shipyard.

5. Storage and handling problems.

Fabricated stiffeners and girders:

1. High strength flanges with ordinary strength webs.

2. Ability to produce high strength structural w/o special heat treatment after fabrication.

3. Save weight and cost.

Coiled Plate: for thinner plating - can reduce cost.

Lapped Joints: For non-critical structures - saves fabrication and erection costs. However, these have been a source of corrosion and fatigue in some applications.

Formed Hopper Knuckle:

1. Eliminates fabrication complexities at outboard bottom comer edges of double hull cargo tankers.

2. Eliminates weld line at this location as a potential source of failure and unreliability.

Structural Standards (6,8)

The introduction of structural standards or standardized designs (9) offers the opportunity for dedicated fabrication techniques and mass production of parts, all with the result of lower construction prices. Reliability should be expected to be enhanced as well. Examples could be in the following areas:

- stiffener spacing
- stiffener sizes
- structural details
- equipment and foundations
- double skin separation
- materials used - strength, toughness, fatigue strength
- aft end design - Eng Rm
- fwd end design - mooring etc.
- transition: double skin to single skin (structural arrangement)
- accuracy

Miscellaneous Inputs (6,8)

Process or peripheral considerations can seriously affect the characteristics of fabrication, and need to be addressed as well. These could include:

Line Heating: Accurate economical and efficient plate bending.

Robotics: Used in welding, painting and paint touch-up, and in inspection.

Developable Surfaces: Structural performance vs. producibility - Use on inner hull and some areas of outer hull.

Welding - develop to improve fatigue performance and increase automation:
- weld contour
- weld heat affected zone
- one-sided welds
- reduced built-in stresses

Heat Forming:

Transition from double to single-skin:
- forward end of cargo box
- aft end, at some location in engine room, such as aft of settling tanks

Numerically Controlled (NC) cut hull penetrations.

Statistical Accuracy Control: The efficiency of mechanization and automation can be enhanced with better accuracy (10). Examples include numerical simulation of heat deformation in burning, welding and bending; mechanization to reduce human error; and three-dimensional measurement of blocks during assembly and at the erection site.

Modular Construction:

- Block and zone definition.
- Work station/Zone information (11).

ALTERNATIVE STRUCTURAL SYSTEM CONCEPTS

General

The strctural elements as discussed in the previous section should then be synthesized into alternative structural system concepts based on their apparent potential for improved producibility. These would then become the candidate alternative system concepts to be utilized in further considerations.

The nature of the alternative structural concepts will be that their principal characteristics are sufficient to establish the entire structural concept for a tanker. That is, they are to consider shell, inner hull, shell stiffening, subdivision bulkheads, and primary hull structure. Some aspects of the alternative concepts may be similar to those already utilized in tanker construction, as these have proven effective. On the other hand, even previously adopted concepts may offer opportunity for optimization as, for example, in the

number of structural pieces or processes employed in fabricating them.

Initial Examples

The types of alternative concepts that may result are described in the following examples:

- o Dished plate hull - The increased strength of plating exhibiting curvature is utilized to eliminate stiffeners. Standard unit sizes result in a building block approach to constructing various hull sizes.

- o Longitudinal framing with formed hopper side comer and corrugated bulkheads - Longitudinal stiffening on shell plating with formed structure for difficult to manufacture and potentially high stress prone areas.

- o Unidirectional stiffening supporting inner and outer shells and corrugated transverse bulkheads - Inner and outer shell stiffening in a single direction along entire hull. Transverse bulkheads supported by stools inboard of the double hull structure.

- o Unidirectional framing on ship sides and conventional double skin firming for deck and bottom as ship sides are more prone to fatigue failures than deck and bottom.

Numerous other alternative concepts and their variants should be synthesized.

Preliminary Producibility Evaluation

In order to identify the potential for improved producibility for each of the alternative concepts prior to their selection for comprehensive evaluation, a subjective analysis should be undertaken at this time.

The characteristics enumerated below have been suggested as an approach to examining a design with regard to Design/Engineering for production for new or unusual designs, or for shipyards without sufficient information to formulate and analyze designs using a formal, quantitative model for comparison (12). It is suggested that alternative designs be examined in the same manner and compared to known baseline designs.

1. Number of unique parts

2. Total number of parts

3. Number, type and position of joints

4. Complexity of design:
   - o simple measuring
   - o simple manual layout
   - o complicated manual layout
   - o CAD/CAM applicability
   - o required manual processing
   - o required machine processing

5. Producibility aspects:
   - o self-aligning and supporting
   - o need for jigs and fixtures
   - o work position
   - o number of physical turns/moves before completion
   - o aids in dimensional control
   - o space access and staging
   - o standardization
   - o number of compartments to be entered to complete work

The number of parts has already been mentioned as an important measure. The type and position of joints for the double skin unit is a critical aspect, as the distance between the inner and outer skins affects access. The adoption of unidirectional stiffeners only between the double skin could allow for a robotic welding system. Innovative construction scenarios will have to be adopted to keep the double skin from negatively affecting the work procedures and work environment, to minimize the number of physical turns/moves, to provide space access and staging and to minimize the number of compartments to be entered to complete work. On the other hand, as the double skin sideshell structure is more rigid and self supporting than the single skin, units of the double skin could provide for easier alignment than single skin sideshell structure, resulting in a reduction in the need for jigs, fixtures and staging.

As a final consideration, special features of the concepts which will enhance pre-outfitting and utilization of machinery modules should be highlighted.

Design Information

The results of these considerations should be a series of alternative structural system concepts for tankers. Each should be described by:

- o An arrangement sketch,
- o Preliminary producibility evaluation,
- o Highlight of principal features which can be tailored to a specific design, and

- o Degree of adaptability to unit construction, pre-outfitting and incorporation of machinery modules.

APPLICATION TO SPECIFIC VESSELS

General

The next step should be the application of each alternative structural system concept to specific vessel sizes deemed to be marketable.

First, a hull form, arrangements, and machinery representative of the size to be considered should be identified. The producibility impacts of these, as they affect structure, should be considered as well. Then, a midship section shouId be synthesized for each structural system concept considered.

The production inputs, including shipbuilding policy, facility dimensions and capacities, and interim product types, should be selected in a manner that can be accommodated by the shipyards. As an example, crane lifting capacity may have to be limited.

The results for each ship and structural system concept will include:

Design

- o General arrangement sketch,
- o Midship section,
- o Scantling plan sketch [longitudinal extent of structure], and
- o Hull form sketch.

Production

- o Outline build strategy including pre-outfitting,
- o Preliminary block breakdown,
- o Zone identification,
- o Material preferences, and
- o Fabrication preferences.

ESTIMATES FOR ALTERNATIVE SYSTEM CONCEPTS

In order to compare the candidates according to the degree they lend to an improvement in producibility, estimates should be prepared for the following characteristics which are known to be measures of producibility and reasonableness of design

- o Contract and detail design manhours
- o Construction manhours
- o Schedule - contract signing to delivery
- o Weight of structure

The design manhour estimates should be based on the same midbody portion of the hull for which weight will be determined. The estimate will be dependent upon the required number of drawings and calculations adjusted to reflect the number of details required, repetitiveness of structural arrangements, unit similarity, pre-outfitting, and incorporation of machinery modules. The design requirements for a more typical tanker should be included as well, for comparison purposes.

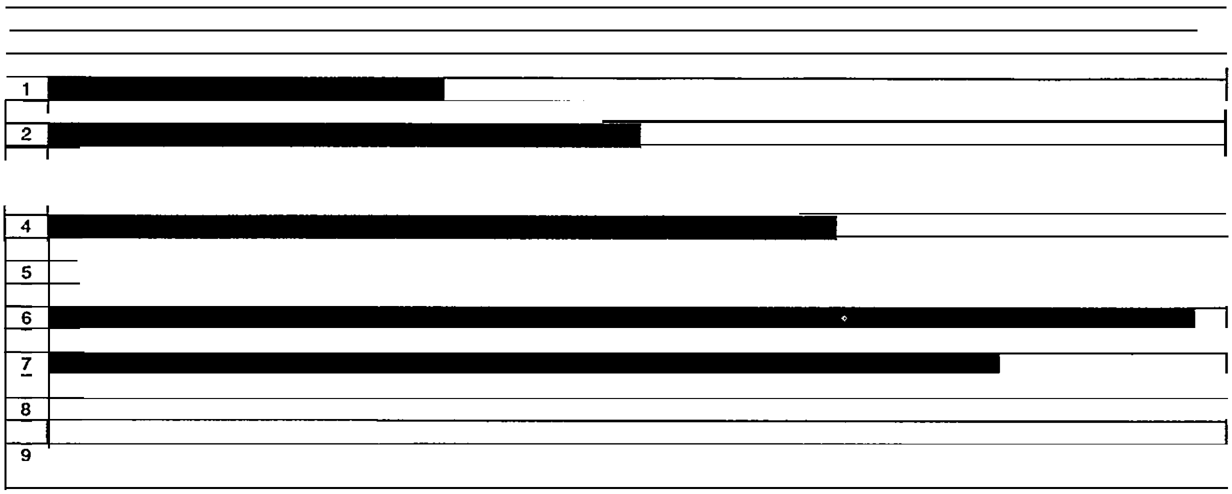
The construction manhour estimate and schedule should consider:

- o Amount of welding,
- o Type and number of frames, and stiffeners,
- o Number of unique parts,
- o Total number of parts,
- o Number, type and position of joints,
- o Self-alignment and support,
- o Need for jigs and fixtures,
- o Work position,
- o Number of physical turns/moves before completion,
- o Dimensional control,
- o Space access and staging,
- o Standardization,
- o Number of compartments to be entered to complete work,
- o Degree to which pre-outfitting and machinery/piping package units can be accommodated,
- o Accuracy control.

The schedule or time line for design and construction will bean essential consideration. Foreign shipyards that are building tankers are now working on schedules from 18 months to 24 months from contract signing to delivery. Examples of past and recent time lines from start of fabrication to delivery are shown in (Figure 5). It should be expected that reduced schedule times will be accompanied by reduced manhours. The impact on schedule of series construction of ships must be quantified as well.

The weight estimate should be a direct take-off from the midship section and scantling plan sketch, and summarized in an appropriate format. The weight of a more typical tanker structure should be provided as well, for comparison purposes.

In an effort to simplify the producibility investigation, yet keep it meaningful, a portion of the



1	285,000 DWT Tanker, Japan, 1993.	6	18,000 DWT Oiler, Navy, 1980, (15).
2	Mobilization Ship, US, 1983, (14).	7	25,000 DWT Oiler, Navy, 1986, (15).
3	Mobilization Ship, Japan, 1980, (14).	8	225m LBP Product Tanker, Denmark, (16).
4	40,000 DWT Tanker, US, 1981, (15).	9	290,000 DWT Tanker, Japan, 1993.
5	40,000 DWT Tanker, US, 1983, (15).		

Figure 5: Fabrication to Delivery Time Lines

hull midbody from keel to main deck, and from one major transverse bulkhead to the next, with structural components as represented in the midship section drawing, should be utilized. This length of hull can then be broken down into all its component plate and stiffener pieces, including brackets and chocks. For each of these pieces the weight, area, and various linear measures of cutting, edge preparation, and welding can be tabulated for each of the alternatives as well.

EVALUATION OF CONCEPTS

The alternative structural system concepts for each of the tanker designs should then be compared with regard to the degree they lend themselves to improved producibility.

Recently, two methods for evaluating the producibility of ship designs and/or ship design .alternatives have been developed under the sponsorship of Panel SP-4, Design/Production Engineering, of the SNAME SPC/NSRP (13). One provides quantitative results in manhours or dollars; the other provides relative results based on weighting factors developed for specific ship projects, and the design phase during which the alternatives are being considered. This latter approach includes evaluation of numerous parameters, including cost, performance, schedule and risk.

SUMMARY

The potential for significant worldwide construction of tankers is near. The time is right for a systematic evaluation of structural concepts for tankers which are advantageous for U.S. shipyards. This scenario represents a unique opportunity to apply the significant knowledge gained through the SNAME SPC/NSRP over the years to a specific ship type.

REFERENCES

1. Daidola, J. C., "Considerations for Earlier Design for Production, " SNAME/NSRP Symposium, 1992, Paper № 6B-2.

2. Okamoto, T. et al, "Strength Evaluation of Novel Unidirectional - Girder - System Product Oil Carrier by Reliability Analysis, " SNAME Trans. 1985.

3. Marc Guardian, Marinex International, Inc.

4. Daidola, J. C., "Tanker Structure Behavior During Collision and Grounding," N.Y. Metropolitan Section SNAME, March 1993.

5. Hofmann, H. A., Grant, R.S. and Fury, S., "Producibility in U.S. Navy Ship Design, " SNAME Journal of Ship Production, August 1990.

6. Communication with R. Kline.

7. Chaffant, A. and Busch, J., "The Rolling of Longitudinally Profiled Plates, " 3rd P. L. A.T.E. Conference, Pennsylvania, USA 1993.

8. Communication with L. Chirillo.

9. Soik, T., "Standardized Designs Within a Shipyard - Basing Decisions on Cost vs. Returns," SNAME/NSRP 1992 Symposium, Paper № 9B-1.

10. Yuuzaki, M. and Okummato, Y., "An Approach to a New Ship Production System Based on Advanced Accuracy Control," SNAME/NSRP 1992 Symposium, Paper № 7B-1.

11. Lamb, T., "Engineering for Ship Production, " SNAME Journal of Ship Production, November 1987.

12. Storch, R. L., Hammon, C.P. and Bunch, H. M., Ship Production, Cornell Maritime Press, 1988.

13. Wilkins, J. R., Jr., Kraine, G. L., Thompson, D. H., "Evaluating the Producibility of Ship Design Alternatives, SNAME/NSRP 1992 Symposium, Paper № 7B-2.

14. Bunch, H. M., "Comparison of the Construction Planning and Manpower Schedules for Building the PD-214 General Mobilization Ship in a U.S. Shipyard and in a Japanese Shipyard," SNAME Journal of Ship Production, February 1987.

15. Nierenberg, A.B. and Caronna, S. C., "Proven Benefits of Advanced Shipbuilding Technology: Actual Case Studies of Recent Comparative Construction Programs", SNAME Journal of Ship Production, August 1990.

16. Anderson, J., Sverdrup, C. F., "Can U.S. Shipbuilders Become Competitive in the International Merchant Market?, " SNAME/NSRP Symposium, 1992.

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New System to Control Magnetic Arc Blow in Welding

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ABSTRACT

Welding of magnetized steels has long been a problem in the welding industry. When welding is attempted in the presence of a magnetic field, the welding arc becomes deflected. This phenomena is known as "arc blow." Arc blow can cause significant weld defects, it can reduce productivity, and it is frustrating to the welder. Sometimes weld joint magnetism is so great that control methods must be used to produce a satisfactory weld.

In 1991, Newport News Shipbuilding developed and built six Magnetic Field Negators (patent applied for) for their welding department. Each unit consists of a small hand-carried electromagnet and power supply that operates off any standard 110/120 volt AC power source. The lightweight system is designed to counteract magnetic fields up to 200 milli-tesla (mT) (2000 gauss) across a 13 mm (.5 in) weld joint in 25 mm (1 in) thick steel.

Through laboratory and production testing, the magnetic field negator has demonstrated the ability to neutralize local areas of high residual magnetism, resulting in a considerable reduction of magnetism-related weld quality problems.

INTRODUCTION

High residual magnetic fields usually occur in alloy steels containing nickel, such as HY-80 and HY-1OO. These fields may enter a material in various ways - they may be induced during the manufacturing process (i.e. rolling, pressing, burning), or by an external source (i.e. using a magnetic hoist). In addition, residual magnetism is often sporadic, unpredictable and concentrated in local areas of a weld joint.

Arc blow occurs when a welding arc is established in the presence of a magnetic field strong enough to deflect the arc. Arc blow can be so severe that it is detrimental to weld quality. Problems such as excessive spatter, wavy bead appearance, lack of fusion, undercut, and porosity are not uncommon (1). Often these defects must be removed and welds repaired, which can greatly increase welding time and cost. Figure 1 illustrates how magnetism can affect weld quality. The figure clearly shows defects such as spatter, porosity, slag inclusions, and rough weld appearance. Arc blow can also greatly reduce productivity and be very frustrating to the welder.

Magnetic field flux density is measured in tesla (lmT= 10 gauss). Generally, welding will progress normally in fields of 2mT (20 gauss) or less. In fields from 2 to 4 mT (20 to 40 gauss), welding can become difficult. About 4 mT (40 gauss), the welding arc can become unstable and in some cases can even blow out (2). Plate thickness and weld joint configuration are two key factors related to field strength levels. For example, welding on a 38 mm (1.5 in) thick plate with a narrow joint bevel will be more difficult than welding a 13 mm (.5 in) plate with a wide joint bevel.

When welding on thicker plate, the welding electrode has more of its length exposed to the magnetic field. In general, arc blow is greatest in the root pass of an open root multi-layered weld joint (3). After the root pass is welded, the magnetic flux will have a complete path in which to travel from one side in aircraft carrier modular construction where large amounts of HY-1OO were used. Weld joints have been recorded with magnetic fields in excess of 150 mT (1500 gauss). Welding at this level would be difficult - if not impossible - without the use of a control method or special technique.

Figure 1. Effects of a residual magnetic field on the root pass of a weld.

of the joint to the other. Therefore, significant amounts of residual magnetism should no longer be present to affect the welding arc.

BACKGROUND

Weld joint magnetism has been a problem at this shipyard and other steel fabricators for years. In the early 1980's, magnetism problems increased in frequency and severity. This increase occurred mostly

In 1986, the shipyard formed a task group to determine causes, document effects, and develop resolutions for weld joint magnetism problems. From this group, several control methods were developed and have been utilized. Some methods were based on inducing a counter magnetic field of equal strength to neutralize the existing field. Other methods attempted to shunt, or direct the field away from the weld joint.

Previously Used Control Methods

The following is a brief discussion of some of the previously used methods identified by the task group.

Neutralizing the Magnetic Field. Wrapping or looping a welding lead around or alongside the workpiece can help control significant amounts of magnetism. This method induces a field that opposes and neutralizes the residual magnetic field. The welder must determine the direction of the residual field and insure that the induced field opposes it; if not, magnetism will compound and increase. Because the welding lead requires close contact with the joint surface to allow for sufficient magnetic couple, the weld joint should be easily accessible, free from fabrication clamps and/or restraining devices.

Electrode Manipulation/Technique Adjustment. The following methods have been used when weak (2-4 mT [20-40 gauss]) arc blow was encountered.

1. Changing the electrode angle.
2. Holding a tight welding arc.
3. Using the gas metal arc process (GMAW) in place of the shielded metal arc process (SMAW).
4. Welding with alternating current instead of direct current.

Identifying Null Locations. Using a gaussmeter or magnetic field indicator, a welder locates sections of the joint where the magnetic field changes direction. Welding starts at these null locations and progresses outward until arc blow is encountered. The process is repeated until the joint is complete or arc blow ceases.

Relocating Welding Ground. Moving the welding ground closer to the joint being welded can sometimes help control arc blow. However, this technique is effective mostly on weak (2-4 mT [20-40 gauss]) magnetic fields. The ground must be from the same machine used for welding. This method is not practical on large weldments.

Shunts. Shunts provide an alternate path for magnetic flux to flow rather than across the root opening. The best shunts are made of low carbon steel and are usually applied to the weld joint as a backing strap. However, shunts do not have to be welded to the joint to be effective. Heat resistant bags can be filled with low carbon steel shot to form a shunt for odd shaped areas. The tighter the shunt is held to the joint, the more effective it will be.

Degaussing. Significant amounts of magnetism can be removed using this method. However, because the machines needed to degauss weld joints are relatively large and require a lot of power to operate, their use is limited.

Each of the control methods listed above had their limitations. They were often cumbersome, time consuming, and produced inconsistent results.

Commercially Available Equipment

One commercially-available magnetism control device was evaluated. The unit negates the field by inducing a counter magnetic field. After extensive laboratory and field testing, several deficiencies were noted. The control unit suffered from high frequency interference, causing erratic operation. The magnetic coil consists of standard welding cable that is wrapped or looped alongside the weld joint. The unit worked fine on long flat joints; however, it was not practical to use if the joint had fabricating clamps and/or

restraining devices blocking access. Additionally, it was difficult to use on joints in the vertical, horizontal or overhead position.

NEW CONTROL METHOD

In 1989, the shipyard sought to develop its own means of controlling arc blow. To be suitable for shipyard use, the system had to meet the following criteria:

1. It should have the ability to produce a strong counter magnetic field.

2. It should be small and portable and allow use on a variety of weld joint configurations.

3. It should be powered by standard 110/120 volt AC.

4. It should be simple to operate.

5. It should be durable when subjected to rough use and elevated temperatures.

Based on this criteria, several prototypes were built and tested. During the testing process, several deficiencies were found that needed to be corrected before the system could be practically used in production. These deficiencies were corrected through an internally funded advanced technology development project.

In 1991, the shipyard completed six magnetic field negating systems for use by their welding department. Each system consists of a small hand-carried magnetic coil and power supply (Figure 2). A counter magnetic field is induced to negate locations of weld joint magnetism long enough for welding to take place. The current model is capable of counteracting a field of 200 mT (2000 gauss) across a 13 mm (.5 in) root opening in steel plate 25 mm (1 in) thick.

Advantages Over Current Methods

While the use of a magnetic coil to control magnetism is not new, the magnetic field negating system has several advantages over previous methods and equipment available.

Portability. The total system weight of the coil and power supply is 7.3 kg (16 lbs), making it easy to transport to the job in a small tool bag. The device operates off any standard 110/120 volt AC power source.

Coil Size and Configuration. The hand-carried coil is 165 mm (6.5 in) long and weighs 4.1 kg (9 lbs). It is designed to fit between most fabricating clamps and/or restraining devices. The magnetic coupling surfaces are configured in a manner which enables them to be used on a variety of weld joints such as butt, tee and inside/outside comer joints.

The Power Supply. The power supply controls the magnitude and direction of the magnetic flux flowing through the coil. It consists of a variable autotransformer, some simple circuitry, and a field direction switch, all contained in an insulated case. An in-line ground fault interrupter is installed for operator safety. The size of the unit is 180 X 130 X 100 mm (7x5x4) and it weights 3.2 kg (7 lbs).

Svstem Operation

The basic step-by-step process to operate the magnetic field negator is as follows:

1. Determine if the magnetic field negator is needed.

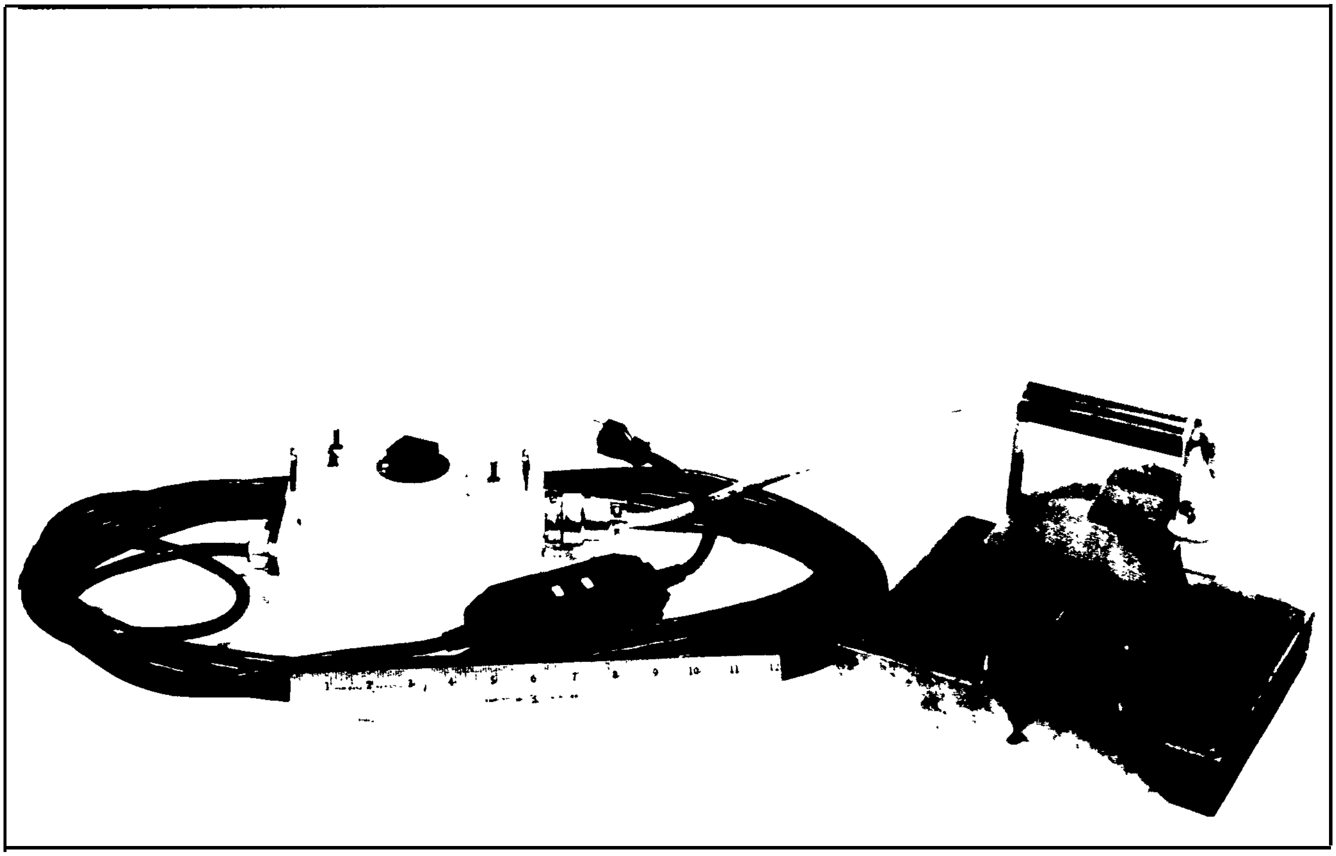

Figure 2. Magnetic field negator system (final prototype) with its coil placed across a weld joint mock-up.

2. Place the coil across the weld joint approximately **25** mm (1 in) from the site where welding will begin. Placement of the device is shown in Figure **3. The** unit can be placed on the back side of the joint if practical. Placement of the coil depends primarily on joint configuration.

3. Using a gaussmeter, measure the magnetic field strength approximately 100 mm (4 in) in front of the coil.

4. Rotate the current control knob to include a counter magnetic field. Note the movement of the field strength on the gaussmeter. If the field reading is increasing, the current polarity is incorrect. Reduce the control current to zero and flip the polarity switch to the opposite direction. Re-adjust the current control knob. Attempt to get the field strength of the joint as close to zero as possible.

5. Remove the gaussmeter probe from the weld joint.

6. Begin welding. Since the negator does not demagnetize the weld joint, it must remain powered during the welding operation.

7. The system will negate the field. Plate thickness, root opening and joint configuration are also factors that affect the reach of the coil. Once the welder starts to move beyond the reach of the coil, arc blow will start to be encountered.

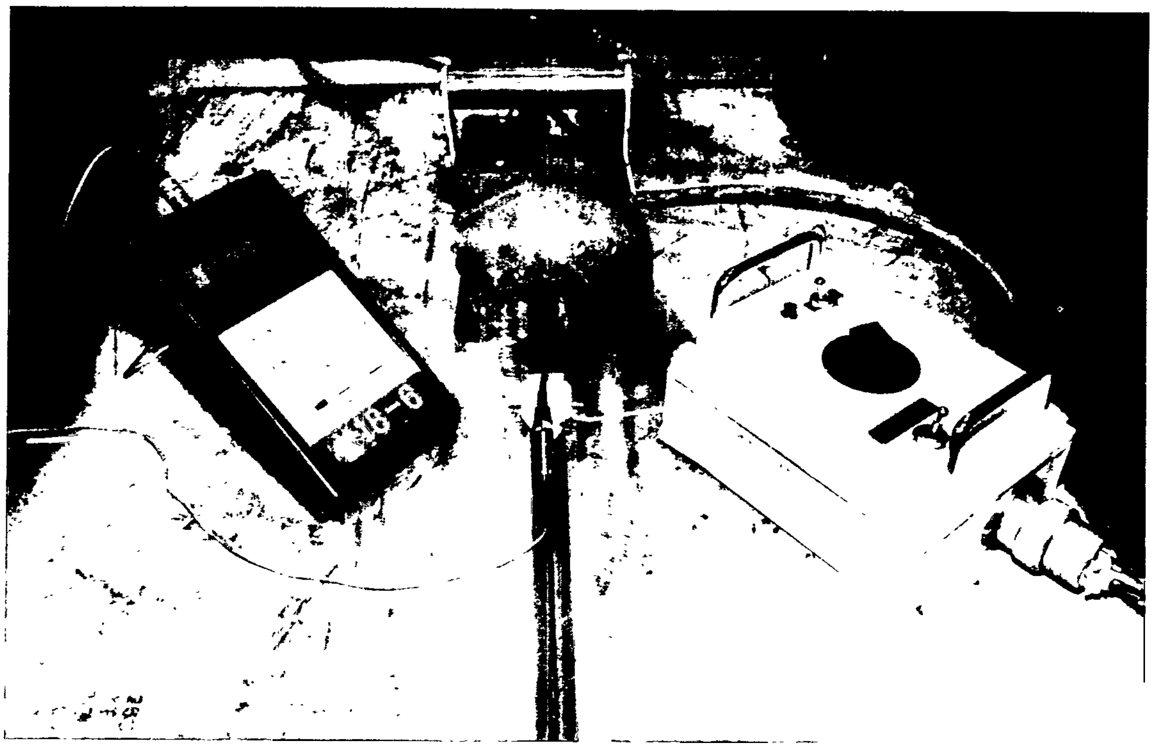

Figure 3. Typical placement of the magnetic field negator and gaussmeter probe across a weld joint.

magnetic field an average of 150 mm (6 in) to 305 mm (12 in) in front of the coil. The "reach" (effective control distance) of the coil will depend on the magnetic field strength of the weld joint. For example, the reach may be 305 mm (12 in) in a 30 mT (300 gauss) field, but only 200 mm (8 in) in a 60 mT (600 gauss) The coil must then be moved closer to the welding arc, and steps 1 through 6 repeated. These steps are repeated until either the root pass is completed, or arc blow is no longer a problem.

Prototype Testing

Testing of the final prototype was

conducted in two locations. A production test was performed onboard ship, while another test was performed in the shipyard's welding engineering laboratory.

Production Test. The device was tested onboard the *USS George Washington (CVN73). In* one case, a magnetized joint on the carrier's main deck was identified by the welding department. This joint had a residual field of 65 mT (650 gauss). Before the magnetic field negator was used, severe arc blow was experienced. After placing the device on the joint, the magnetic field was reduced below 1 mT (10 gauss). When welding resumed, no visible arc blow was detected.

Laboratory Test. A test joint was magnetized to demonstrate the field negator's effectiveness. The joint was fabricated using 25 mm (1 in) thick HY-1OO -610 mm (24 in) wide by 915 mm (36 in) long. The joint used was a B2V. 1 (single sided vee bevel) with a 3 mm (.125 in) root opening. A Magnaflux CRV-12 magnetic particle inspection machine was used to induce a magnetic field into the joint. Using a gaussmeter, magnetic field readings were taken every 25 mm (1 in) along the entire joint length. The average measured magnetic field was 35 mT (350 gauss). Then the field negator coil was placed across the weld joint in the location of the highest gauss readings. The field negator was adjusted until a point 150 mm (6 in) in front of the coil obtained a near zero reading. Magnetic field readings were taken again from the base of the coil to 300 mm (12 in) in front of it. The root pass of the test joint was then welded. Figure 4 illustrates improvement in weld

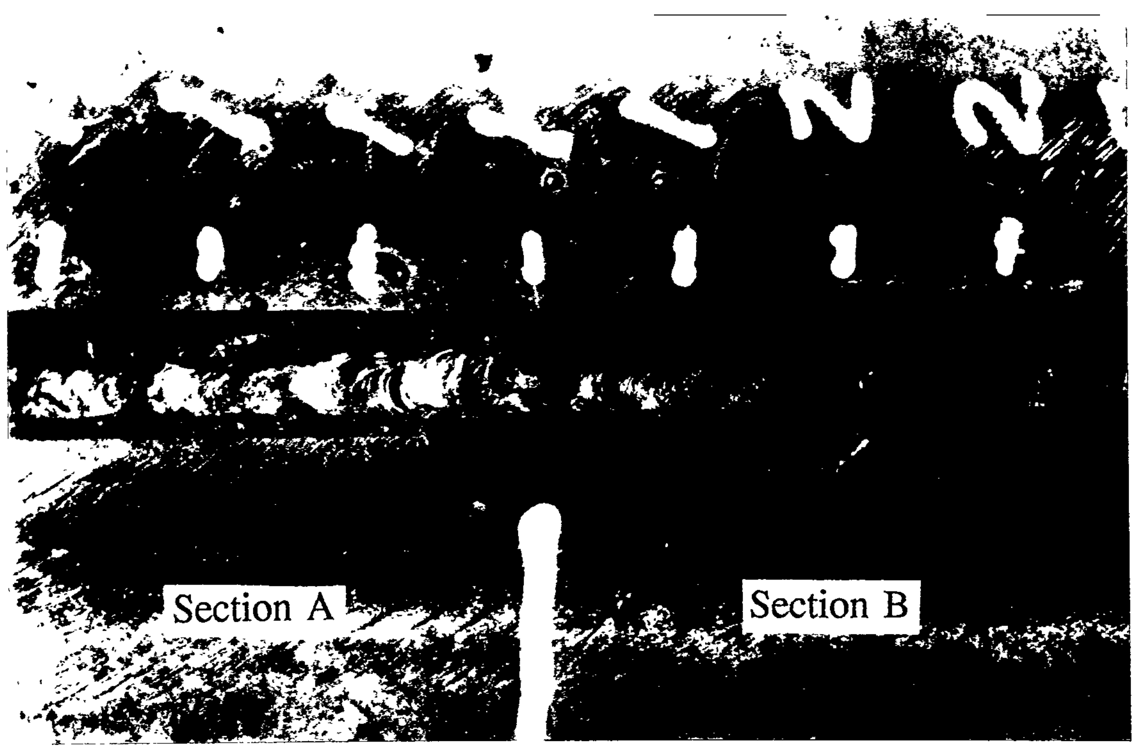

Figure 4. Difference in weld quality between a root pass welded with (section B) and without (section A) the assistance of the magnetic field negator.

quality when the magnetic field negator was used. Section A of the figure was welded first in the presence of the residual magnetic field; while section B was welded with the aid of the field negator.

Test Results

Both the production and field tests produced favorable results. Prior to neutralizing the magnetic field, severe arc blow was encountered when welding was attempted. After energizing the field negator, arc blow was greatly reduced or eliminated; resulting in improved arc characteristics and weld bead appearance. Figure 5 demonstrates the field negator's ability to significantly reduce the residual magnetic field in the laboratory test joint.

Magnetic field readings do not need to be monitored during welding. Tests have shown that observing the stability of the arc is a good way to determine the needed adjustment to the field negator. However, the residual field should be monitored from time to time with a gaussmeter or field strength indicator to determine when the field changes polarity. In addition, if a gaussmeter is not available, magnetic particle testing powder can be used to determine when the magnetic field

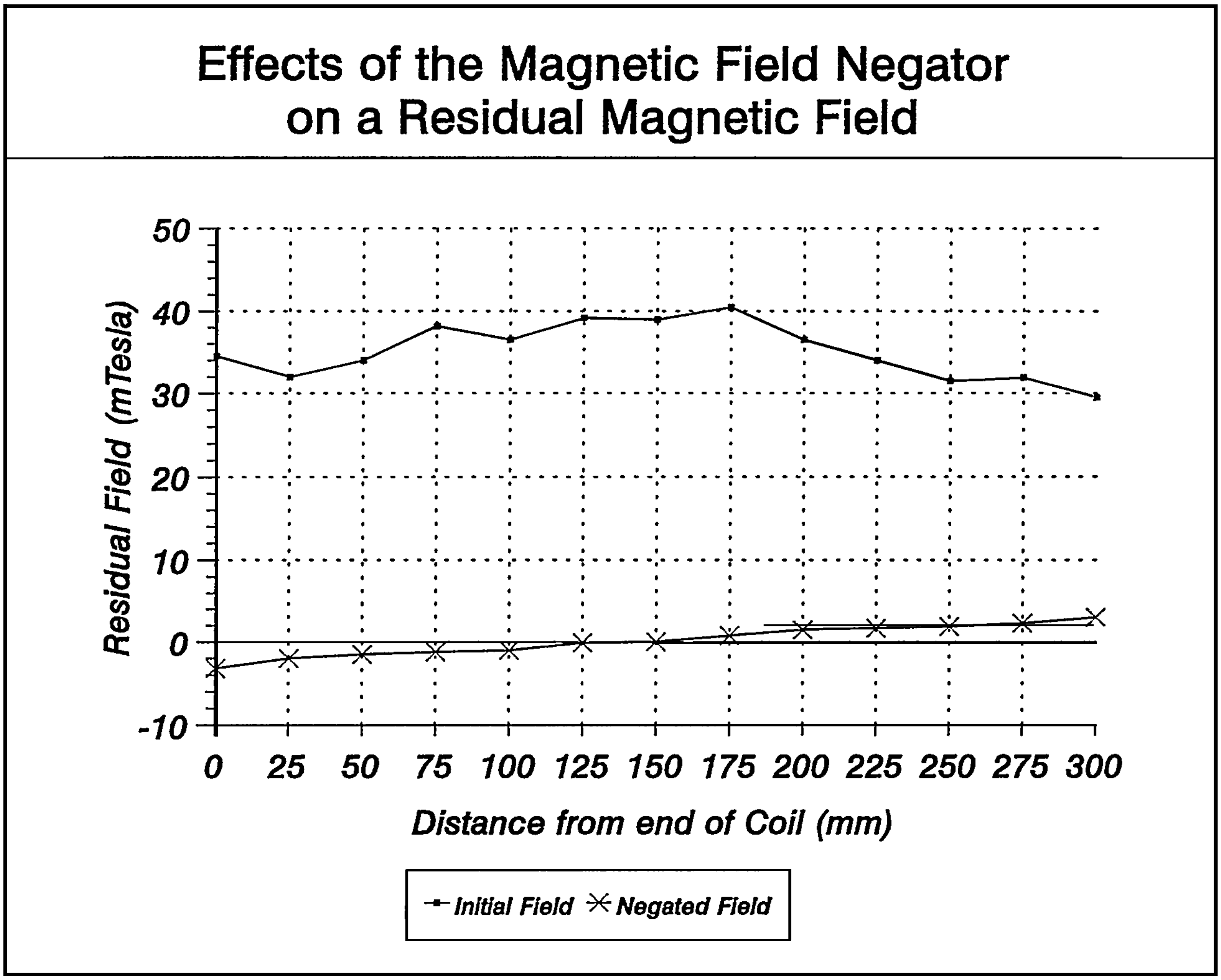

Figure 5. Comparison of the residual magnetic field before and during use of the magnetic field negator.

negator has neutralized the residual field in the weld joint. The powder will initially adhere to the sides and root opening of the joint; when the field has been negated the powder will fall out.

Limitations

While the magnetic field negator has several advantages over the previous control methods used, it has its limitations.

1. The system does not degauss the weld joint; once power is removed magnetism will return to the joint

2. The device will only neutralize small lengths (200 mm [3 in] to 300 mm [12 in]) of residual magnetism. It may have to be moved many times if welding a long magnetized joint.

3. Caution must be used when using the device in the horizontal, vertical or overhead position. If power is inadvertently shut off, the unit could fall, possibly causing injury to the operator.

CONCLUSION

Magnetic arc blow can be one of the most frustrating problems a welder can experience. When arc blow is encountered, weld quality can suffer. Until now, control methods or techniques *were* limited, cumbersome, time-consuming, and produced inconsistent results. On the other hand, tests have shown that the new device has the ability to consistently negate local areas of high residual magnetism. After production and laboratory tests were conducted, the following conclusions were drawn.

1. The magnetic field negator is effective in minimizing weld joint magnetism, thus preventing arc blow.

2. The system is lightweight and portable. It operates off any standard 110/120 volt AC power source, allowing use at most any location. It can be used on a variety of weld joint configurations. The system's simple design allows easy operation with minimal training. The device is durable and able to withstand the harsh shipyard environment.

REFERENCES

1. The Procedure Handbook of Arc Welding, 12th edition, Cleveland, The Lincoln Electric Co., 1973, (pp. 3.2-1-3.2-5).

2. P. J. Blakely, "Magnetic Arc Blow - Causes, Effects and Cures". Metal Construction, February, 1988.

3. "Magnetic Arc Blow", TWI Connect, October, 1992.

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Naval Ship Affordability Through Machinery Modularity

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ABSTRACT

The shipbuilding industry has recently taken an increased interest in modularity of machinery and equipment. Through modularity, decentralization of key items such as combat, auxiliaries and propulsion equipment is more feasible. Zonal or compartmental machinery modules often lead to reduced ship volume and hence ship costs. Modularity may also lead to standardization within a ship, a ship class, or across several ship classes. The reward for implementing modularization is partly found in labor savings. Production of modules by moving the installation and construction from the ship or from the blocks to an off-ship shop generates some savings. However, this labor saving must be weighed against the material and labor cost of constructing the module container. The modules may take up increased space compared to a conventional unit, which would cause the ship size and cost to increase. This paper intends to quantify these tradeoffs to determine if it is beneficial to ship affordability to employ any of a series of modularity concepts. The concepts studied include modular propulsion, payload (combat system), auxiliary and habitability installations.

INTRODUCTION

There is an ever growing interest in modularity and commonality to reduce naval ship production costs and improve affordability. The emphasis of the study presented in this paper is to define a set of modularity concepts, and then assess them on a cost and affordability basis, to sort out the attractive approaches for future designs. This study is an initial conceptual level evaluation only. Commonality within the ship and ship class will be achieved, but commonality across several classes will be left to future study. The modularity concepts selected will generally be decentralized units needed in some quantity for each ship ,so that they will be common within the ship and the ship class. Thus, both the advantages of off-ship production and quantity production of standardized units will be weighed against modularized unit construction costs and the ship size(volume) influences of using modules.

The modularity concepts which have been considered for use in combatant ships are propulsion modules called powerpaks, zonal auxiliary modules, zonal auxiliary and power generation modules, compartmental auxiliary modules, compartmental auxiliary and power generation moduldes, habitabilty modules, modular combat system elements and combined propulsion, power generation and auxiliary machinery modules.

A zone as referenced in the zonal concept is the volume from the hull up through the superstructure between two watertight bulkheads. A compartment is the volume between two watertight bulkheads on one deck level. Typically, there are ten to thirteen zones on a destroyer and thirty to fifty compartments.

CONCEPT DEFINITIONS

Propulsion Module (Powerpak)

Although the currently used LM-2500 gas turbine engine is packaged in a module for installation, it could be further modularized by including the engine, a reduction gear box, and the ancillary equipment in a module. Much of the installation cabling and piping would be installed in a shop. This concept facilitates testing before shipboard installation. Installing an entire powerpak module in the engine room as a unit reduces the installation labor. Figure 1 illustrates a powerpak unit.

Zonal Auxiliary Modules

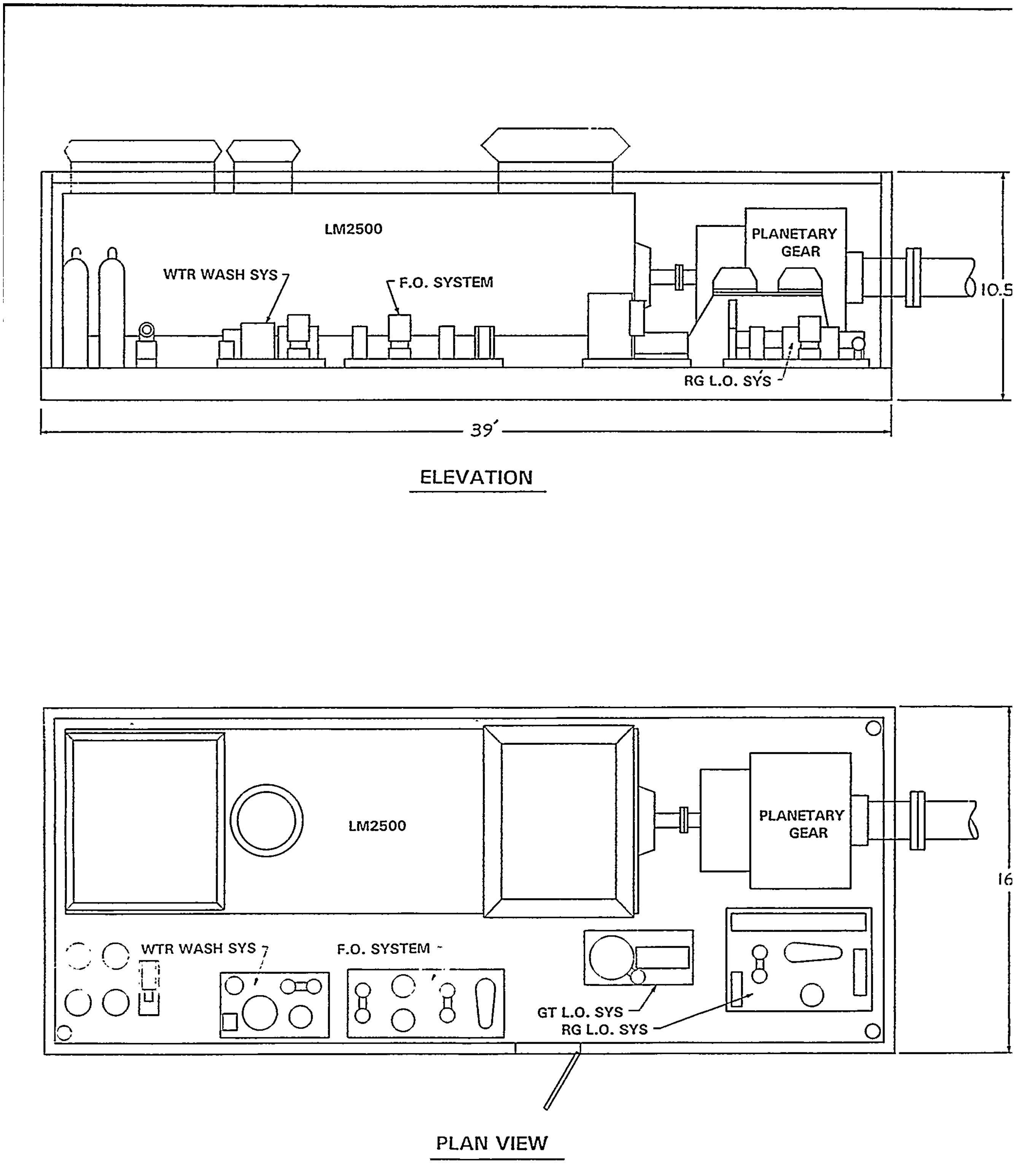


Figure 1. Powerpak Module

A zonal auxiliary module may include one or more of the auxiliary units required for a zone. Several zonal modules maybe used in each zone for different auxiliary systems. There could be a zonal fire pump, zonal sea water pump and zonal HVAC units, all mounted separately in a zone or combined in one or two units. A desalination unit could also be added as well as an air compressor where needed.

The fire pump, HVAC and saltwater pump units would be standardrized for the ship. The zonal units would be cross-linked to provide redundancy for a damaged or failure condition. For example, the HVAC unit would have an eighty ton capacity for a large destroyer. Figure 2 illustrates a typical zonal module.

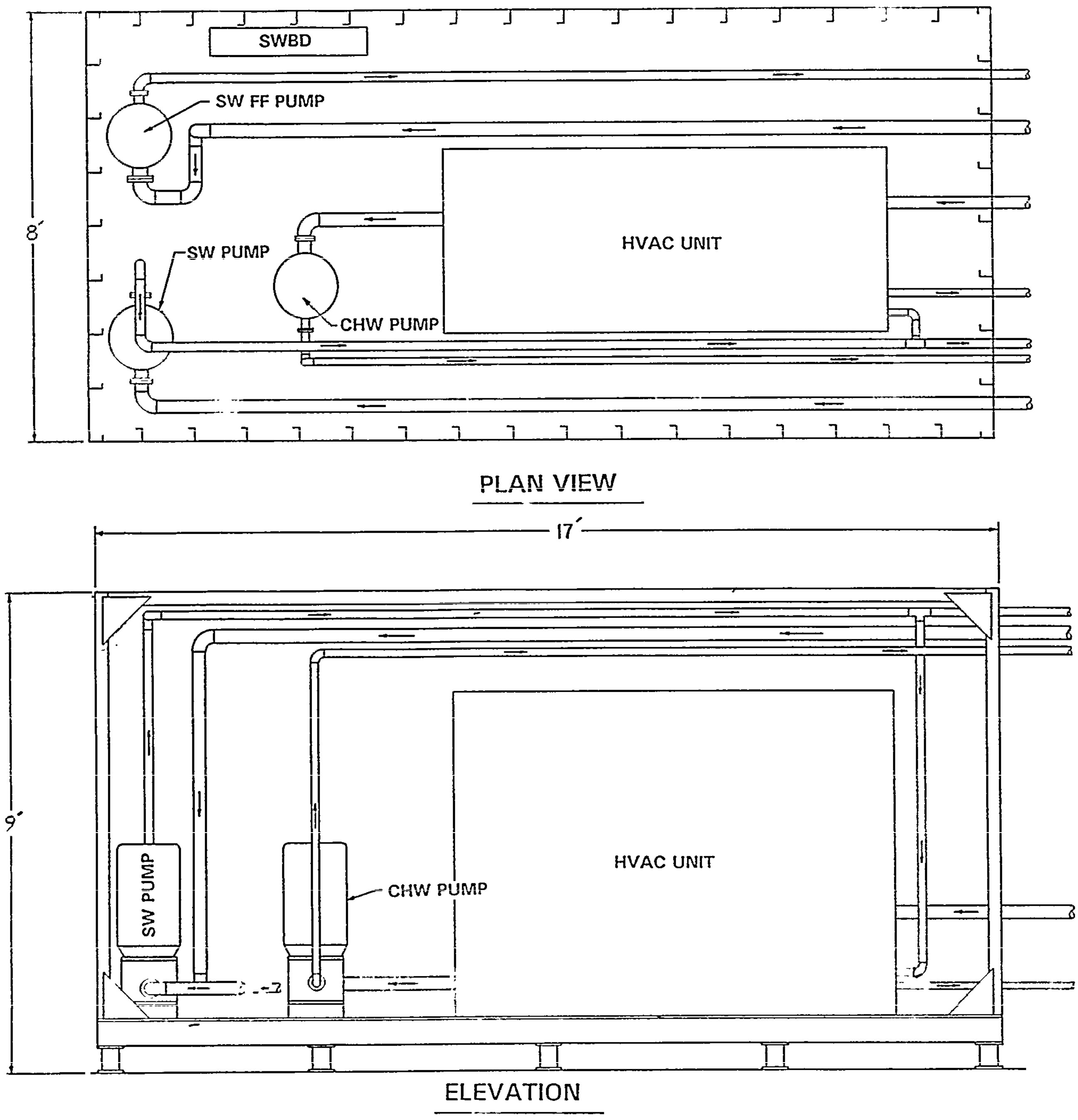


Figure 2. Zonal Auxiliary Module

The use of zonal auxiliaries eliminates the need for specialized auxiliary rooms. If the modules can be efficiently arranged in the ship, volume savings can be achieved. Studies indicate that the savings are on the order of five percent of the ship volume.

Zonal Auxiliary Power Generation Module

When a small gas turbine or diesel generator is added to the zonal modules, all of the power/auxiliary functions can be favorably located as needed in each zone. These units are standardized. Multiple units generally would be required in the zones using the most power, such as zones where major combat system elements are located. However, most zones would require only one unit. the units could be integrated with the HVAC unit into one module. It is likely that pump modules would be located low in the ship near the inner bottom, while the HVAC and power modules would be located near the main deck where the needed air enters the ship. There is a significant ship volume reduction of about ten percent gained by using this concept because of the elimination of auxiliary and generator spaces. Figure 3 illustrates this type of **modular installation.**

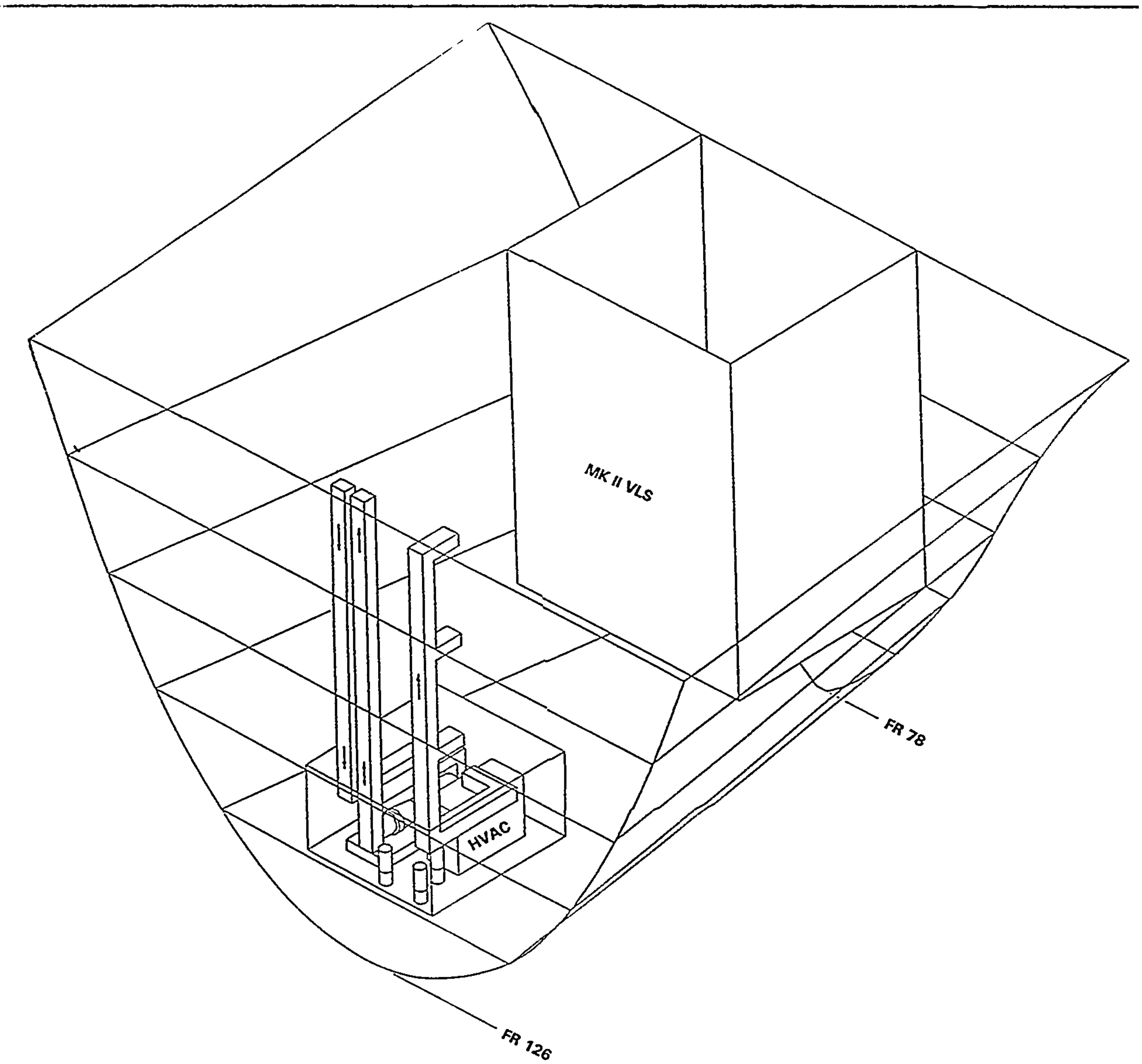


Figure 3. Installation of Zonal Auxiliary/Electric Module

Compartmental Auxiliary Modules

Comparmental auxiliaries are limited to compartmentalizing the HVAC units. The pumps and compressors are zonal because they need to be located near the water source. The HVAC units are small and could be. mounted in the overhead. These units will be built in quantity so standardized production is of benefit. The volume reduction expected is not as much as for zonal units, but a two and a half percent saving is expected. Figure 4 illustrates a compartmental installation. Figure 5 shows one of these units.

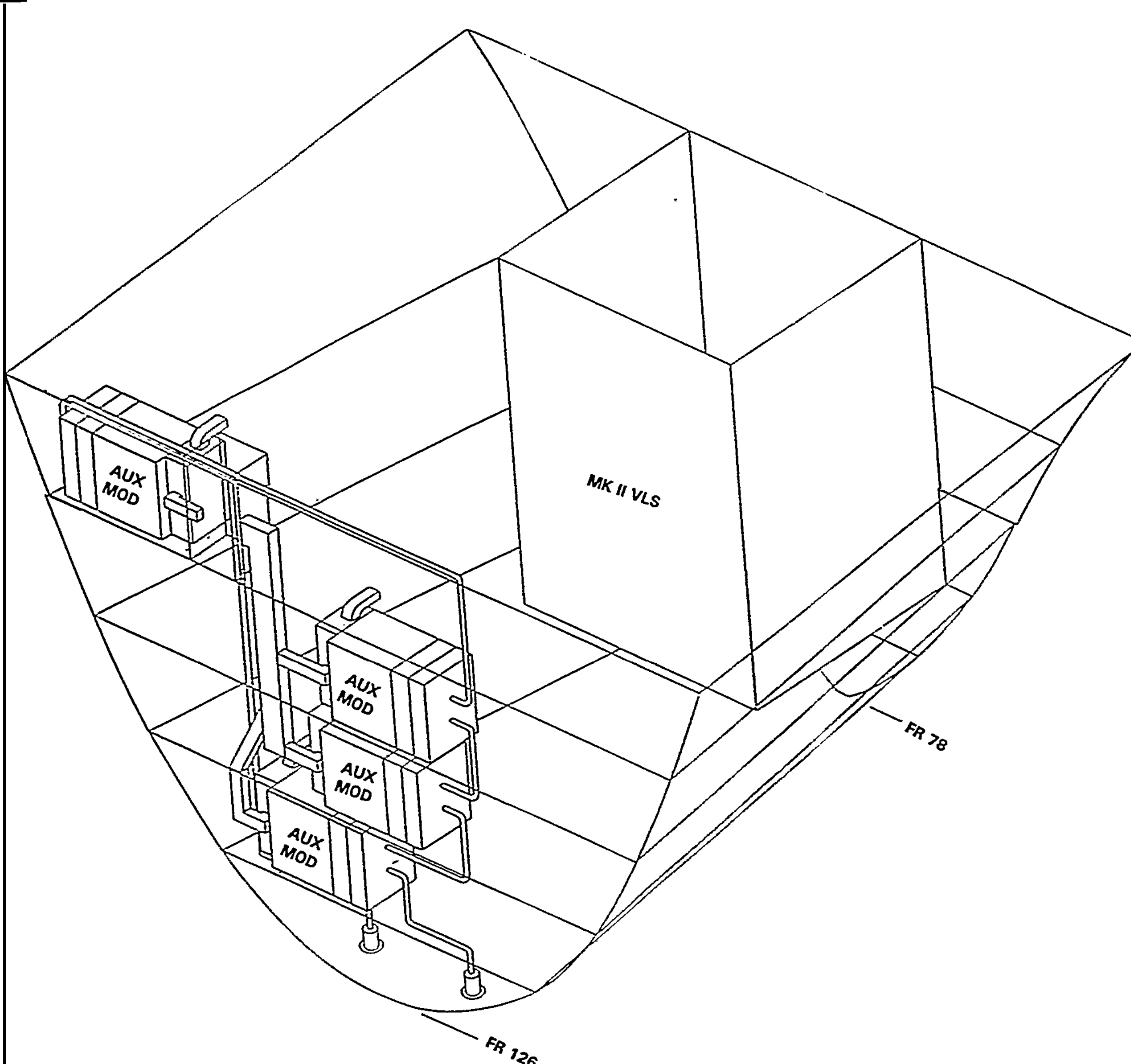


Figure 4. Installation of Compartmental Auxiliary Module

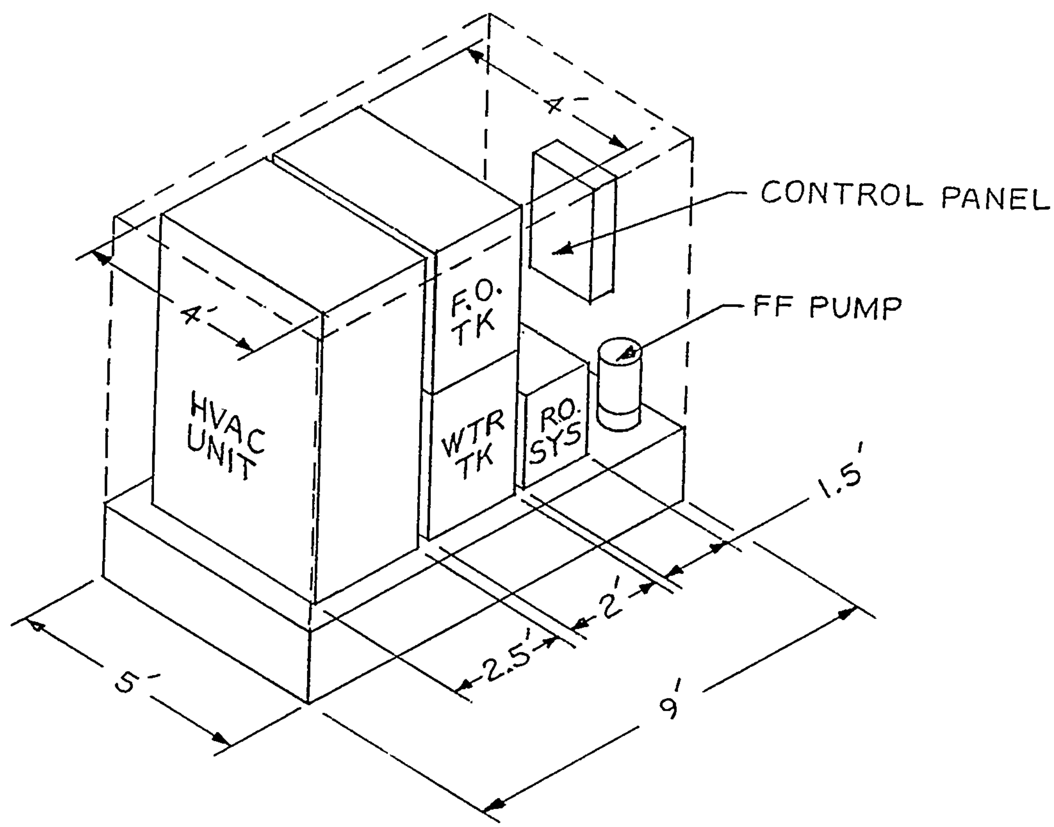


Figure 5. Compartmental Auxiliary Module

Compartmental Auxiliary Power Generation Module

When a small diesel generator is added to a module, the auxiliary and power generation equipment is located efficiently in each compartment. Figure 6 illustrates this concept. The volume reduction gained by this concept is about

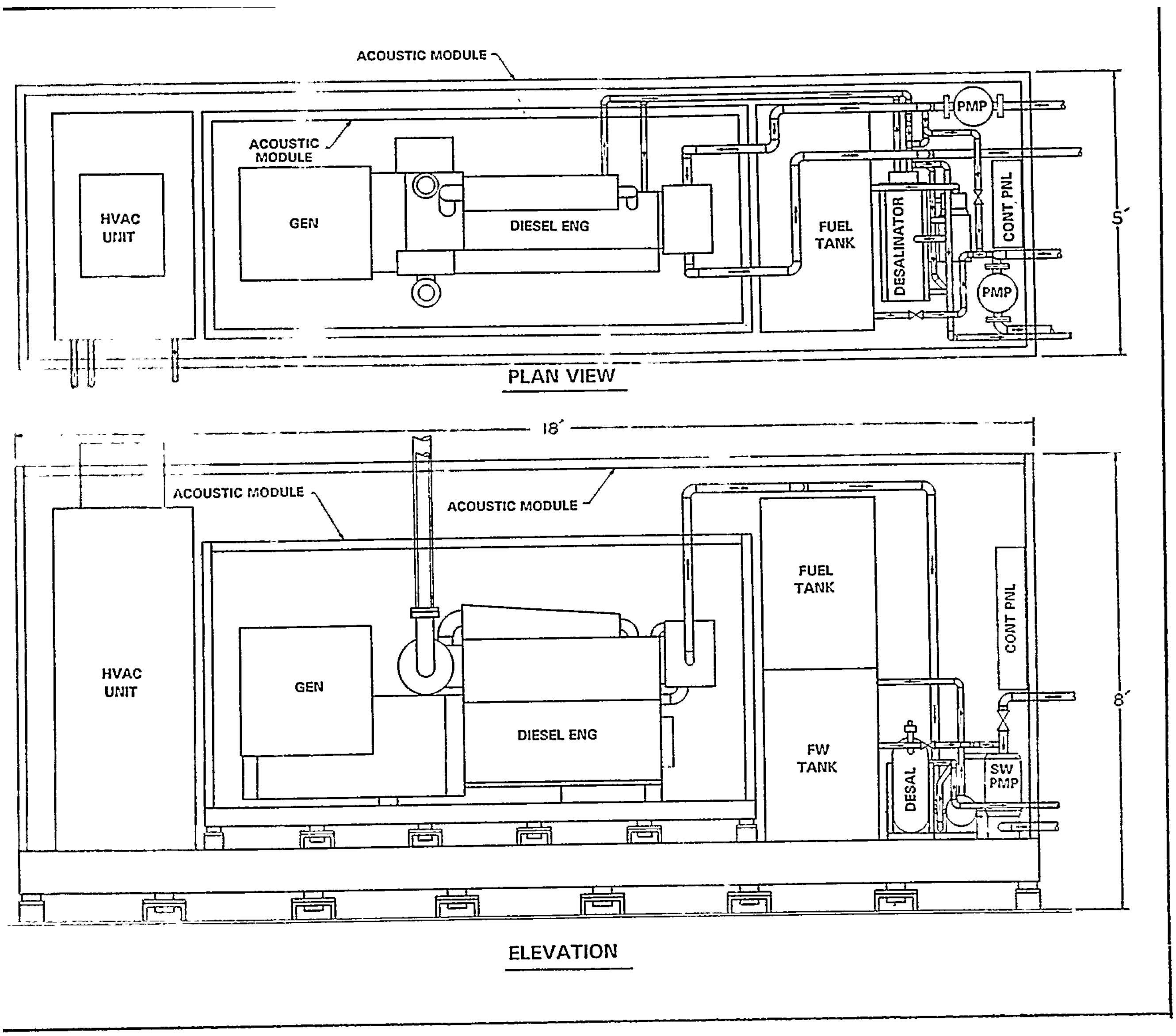
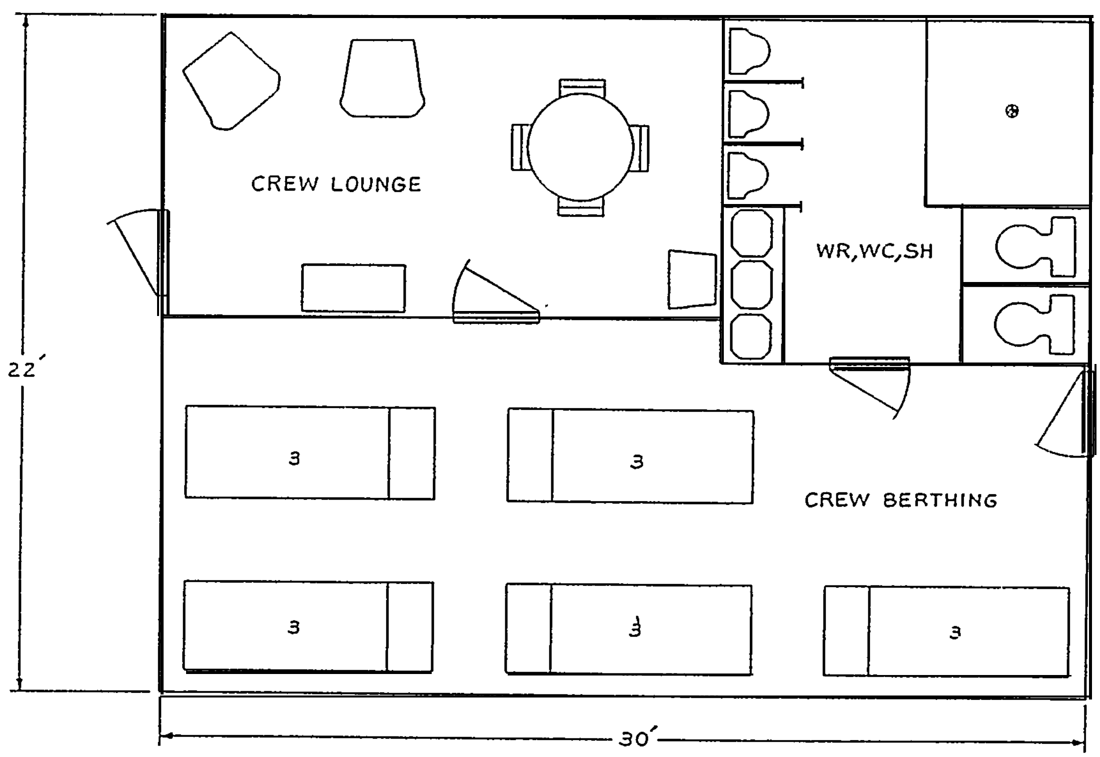


Figure 6. Zonal Auxiliary/Electric Module

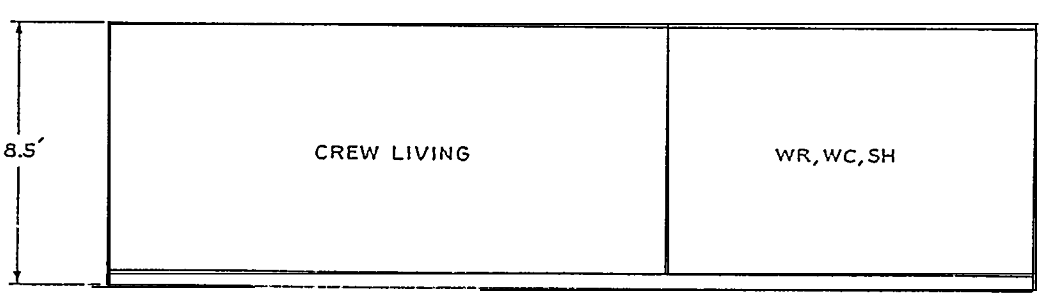
seven percent of the ship volume, based on arrangement studies.

Habitability Modules

Outfitting of equipment associated with crew berths, offices, galleys, mess rooms, etc. can be accomplished in modules. The modules can be somewhat standardized. Figure 7 illustrates a crew living module. The module has a foundation of non-structural bulkheads. Decking, lighting and cables are installed in the modules in a ship. However, ship layout studies have shown that fitting the best optimized size assortment of modules in a combatant leads to a seventy-five percent volumetric **efficiency. This is** a significant volume penalty. If non-standard modules are used, then this penalty can be reduced, but there is still a significant penalty. the volumetric penalty has to be balanced against the labor savings from standardized shop construction.



Plan View



Elevation

Figure 7. Crew Living Module

Modular Combat Systems

Vertical Launch Systems (VLS), guns, radar units, etc. can be outfitted in modules for ease of outfitting and testing. The principal ship influence of using modules is a six percent increase in combat system unit volumes. The weight penalties are small, since many of the combat system elements are already palletized.

Combined Propulsion/Power Generation/ Auxiliary Modules

These modules are located in four or six zones toward the center of the ship. The module contains a mid-size gas turbine (i.e. LM-1600 or 571 KF) driving a waterjet through a gearbox, a propulsion derived ship service generator (PDSS generator), and auxiliaries such as the pump units. The waterjet intake and exhaust nozzle are attached separately. The waterjets can be operated singly, in pairs, or in all units operating for good performance loading control. The HVAC unit can also be included in the module. The HVAC units provide chilled water for distribution as needed. The concept is shown in Figure 8.

DISCUSSION OF ZONAL AND COMPARTMENTAL OUTFITTING

Zonal and compartmental units have advantages and disadvantages. These attributes are documented in several references. Reference (1) shows that zonal fire pumps lead to significant weight and cost savings. Reference (2) shows that zonaI electrical systems also have major savings in weight and cost. The lengths of piping and cable are significantly reduced. A recent report (Reference (3)) compares zonal and compartmental HVAC. Zonal HVAC demonstrates the greater cost savings. Compartmental auxiliary modules also provide cost savings, but zonal systems have lower total equipment cost. Zonal and compartmental systems offer excellent reliability and availability through redundancy, but will probably require more preventative maintenance manhours. The zonal and compartment boundaries can be better protected against fire spread because of the fewer bulkhead penetrations.

In general, the unit or component weights go up for zonal/compartmental systems, but decreases in piping, ducting and cable weights more than offset these increases. The weight reductions are on the order of fifteen to twenty-five percent. Similarly, cost reductions of ten to twenty percent are indicated.

The dispersed nature of the zonal and compartmental systems leads to improved ship survivability and battle damage control. Zonal and compartmental modules should be easier to build and install than their centralized counterparts. The maintenance for each unit should be less, but the larger number of units will probably increase the total manhours per year.

MODULARITY INFLUENCES

Module Characterization

A computer model was developed to design and cost modules based on size and weight of equipment installed. A bedplate was sized to carry the lifting loads on the module. The enclosure was sized and weighed to provide an acoustic enclosure taking no structural loads. Habitability modules are different in weight and size than machinery modules because of the bedplate loads. The non-structural sidewalls are the same and are weighed and calculated by the following factors

Weight	28 lbs/square foot
cost	$31 /square foot
Labor	2.25 hours/square foot

Learning Curves

Repeated construction of common or standard modules leads to improved efficiency, generally characterized by a learning curve. A ninety to ninety five percent labor learning curve is typical. A learning curve is defined as the fraction or percentage multiplier when the quantity manufactured is doubled For example, the labor for an item is reduced by x.95 going from eight to sixteen units if there is a ninety five percent learning curve. A general labor multiplier can be computed for any case by the equation:

$$TF = \sum_{x=1}^{x=N} (LF)^{\log x/\log 2} \qquad (1)$$

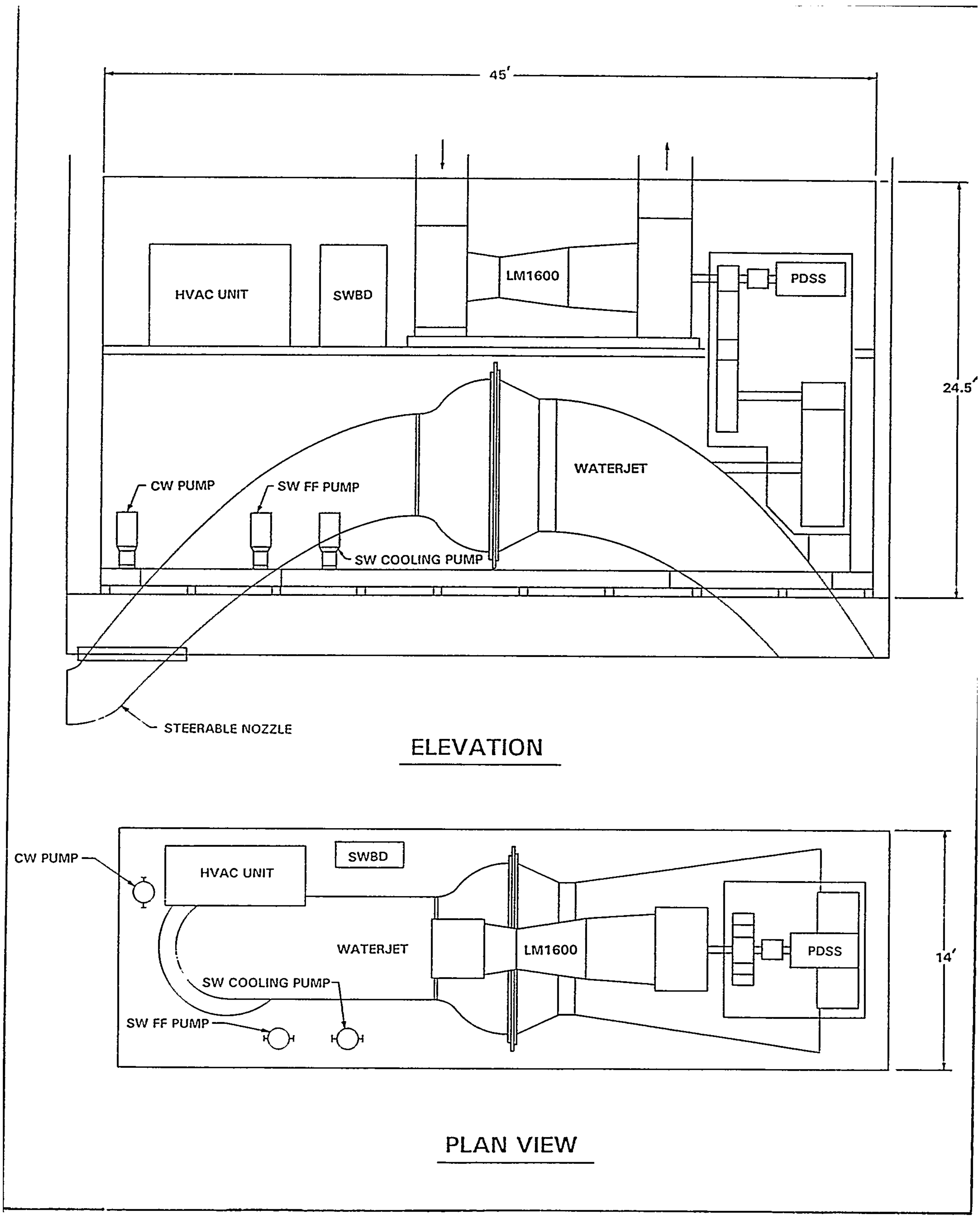


Figure 8. Propulsion/electric/auxiliaries Module

where

x = counting variable
LF = learning curve factor
N = number of units built
TF = total learning factor

TF multiplied by the labor for the first unit gives the labor total for all N units.

Shop Construction

Labor performed for a given construction task in a shop has been shown to be markedly less than required to perform the same task on board a ship. Shipyard surveys have shown a wide variety of results for the reduction factors. The table below indicates the ratios from blocks to shop, and ship to shop, from a conservative and optimistic viewpoint.

	Conservative	Optimistic
Block/shop	2/1	3/1
Ship/shop	3/1	4/1

Optimistically, the labor for a task on a ship could be performed in a shop with one-fourth of the labor hours, while a task on the blocks could be accomplished with one-third of the labor hours. Conservatively, the reductions are one-third shop to shop and one-half blocks to shop. The conservative values are used in the affordability analysis to follow.

Habitability and combat system modules use the ship/shop ratio, while the machinery modules use the block/shop ratio in the labor reduction analysis.

SHIP INFLUENCES

Affordability Analysis

An affordability analysis procedure has developed over the last few years to express the relative affordability of a new approach or concept applied to a ship when compared to a baseline ship. Both acquisition and operating costs are included in a discounted life cycle cost analysis. A ten percent discount rate is used. A future dollar value in year N is reduced by the ratio $\{1/(1+ .1)\}^N$ to give its present value. A standard scenario is used in the analysis as follows:

- 100 ships are constructed, 5 per year for twenty years,
- Ship funding begins five years after program initiation,
- Ships are delivered five years after funding,
- Ships operate for forty years after delivery.

Affordability is then defined as the number of ships which can be acquired and operated for the same discounted budget as 100 baseline ships.

Baseline Ship

The baseline ship for study is the DDG-51. This ship was chosen because of its familiarity to the naval engineering community

Analysis Method

The acquisition cost and affordability analyses are carried out by using a ship design and cost model. The model uses weight and volume iterative loops to size the ship, while the payload and ship performance are held constant. The ship particulars are then computed, including hull dimensions, ship weight breakdown, etc. Once these particulars are computed, the ship acquisition cost is computed by adding labor and equipment costs. The operating and support (O&S) cost is also computed, including annual crew, fuel, maintenance, and training costs. These costs are based on ongoing naval O&S cost data. A separate affordability model then computes the discounted life cycle cost and affordable fleet size compared to 100 baseline ships.

Acquisition Cost Results

Each of the modularity concepts described above was evaluated on any acquisition cost and affordability basis. The ship cost results are shown in Table I. The ship acquisition cost results are plotted in Figure 9. The results are indicated as differences from the baseline ship acquisition cost for a single ship. The ship costs are the average costs over thirty ships. The results are also broken down into changes due to each contributor as listed below

1. Ship/shop or block/shop labor reductions,
2. Learning curve reductions,
3. Cost of module construction,
4. Ship change costs including piping, wiring, volume and weight changes.

These result breakouts are shown on Table II.

These results do not include changes in operating cost.

Baseline	Powerpak	Habit-ability	Zonal Aux.	Zonal Aux/Elect	Compart Aux	Compart Aux/Elect	Propulsion/Power/Auxiliaries
829.84	830.68	853.49	840.71	808.36	796.42	751.56	771.06

Table I. Ship Acquisition Cost Comparison (millions of dollars)

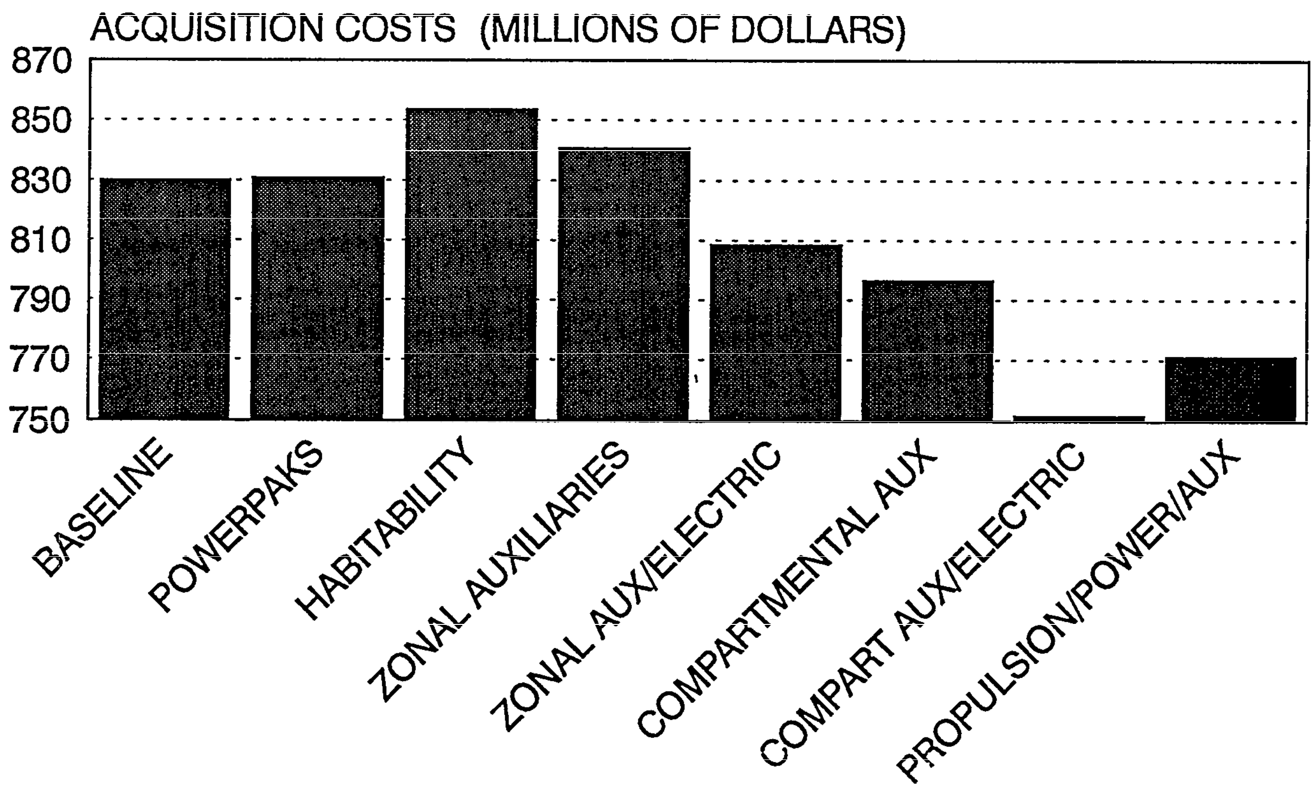


Figure 9. Ship Acquisition Cost Comparison

	Powerpak	Habitability	Zonal Aux	Zonal Aux/Electric	Compart Aux	Compart Aux/Electric	Propulsion/ Power/Aux
Ship/shop	-1.05	-3.27	0.00	-1.12	-0.41	-0.39	-1.07
Learning	-0.18	-0.44	0.00	-0.27	-0.12	-0.12	-0.21
Modules	2.07	11.76	7.05	3.08	3.63	3.81	5.63
Concept	0.00	15.60	3.82	-23.17	-35.73	-81.58	-63.13
Overall	0.84	23.65	10.87	-21.48	-33.42	-78.28	-58.78

Table II. Cost Sensitivities (in millions of dollars)

The powerpak concept shows little advantage from learning or block/shop labor ratios. The cost of the modules is significant. The use of the powerpak has little ship volume significance. Overall, the powerpak is slightly more expensive. However, the powerpak concept maybe useful for improved noise isolation and survivability.

The zonal auxiliaries concept is attractive due to reductions in piping and auxiliary room space. The other factors are of small consequence.

The zonal auxiliary/electrical power generation concept is similarly benefited by a smaller volume, and less piping and cable. Fuel savings are also beneficial.

Compartmental auxiliaries and compartmental auxiliaries/power generation both have large paybacks due to volume, cable, ducting, and piping savings. The other influences are negligible.

Habitability modularity is a poor cost performer, resulting in considerable ship cost increases. These increases stem horn the volume inefficiency of the modules and the additional cost of the modules themselves.

Modular combat system elements are not cost effective for the same reason as the habitability modules. The space and module cost penalties overshadow some of the other advantages. Modular payloads are of most benefit for ease of modernization and rapid change out of combat elements.

The propulsion/power/auxiliaries module is one of the most cost effective concepts. Again, the volume, piping and electrical wiring savings make up the major elements of the cost savings.

Affordability **Results**

Using the affordability analysis methods described previously, the relative affordabilities of each concept were assessed. Table III shows the ship cost and affordability results. Figure 10 plots the affordability results. The ship concepts of advantage have affordable fleet sizes greater than one hundred. The zonal and compartmental concepts plus the combination machinery module show major improvements in affordability compared to the baseline DDG-51. Powerpaks are neutral, while habitability and payload modules are affordability drawbacks.

CONCLUSIONS

With a steadily decreasing naval ship acquisition budget, cost saving and producibility improvements are of great interest. This study has shown that several machinery concepts can lead to major savings. These savings are mostly due to reduced ship size and outfitting, rather than the use of standard modules constructed in a shop. Habitability modules and payload modules show a negative cost advantage because of their volume inefficiencies.

REFERENCES

1. **Shiffler,** Mark, "Development of a Zonal Architecture Fire Main System for Combatant Ships," Naval Engineers Journal, May, 1993.
2. Petry, Chester R. and Rumburg, Jay W., "Zonal Electrical Distribution Systems: An Affordable Architecture for the Future," Naval Engineers Journal, May, 1993.
3. "Zonal versus Compartmental Auxiliary Systems," Decision Engineering Report, March, 1993.

Concept (Modules)	Average Acquisition Cost (M$)	Operating and Support Cost (M$/yr)	Affordable Fleet Size
Baseline	**829.8**	17.15	100.0
Powerpaks	**830.7**	17.23	99.9
Zonal Auxiliaries	**808.4**	16.24	103.0
Zonal Auxiliaries/Power	**796.4**	14.94	105.3
Compartmental Auxiliaries	**772.8**	15.59	107.7
Compartmental Auxiliaries/Power	**751.6**	13.89	111.7
Habitability	**853.5**	18.19	96.9
Combat System	**840.7**	17.56	98.6
Propulsion/Power/Auxiliaries	**771.1**	14.23	108.9

Table III. Ship Cost and Affordability

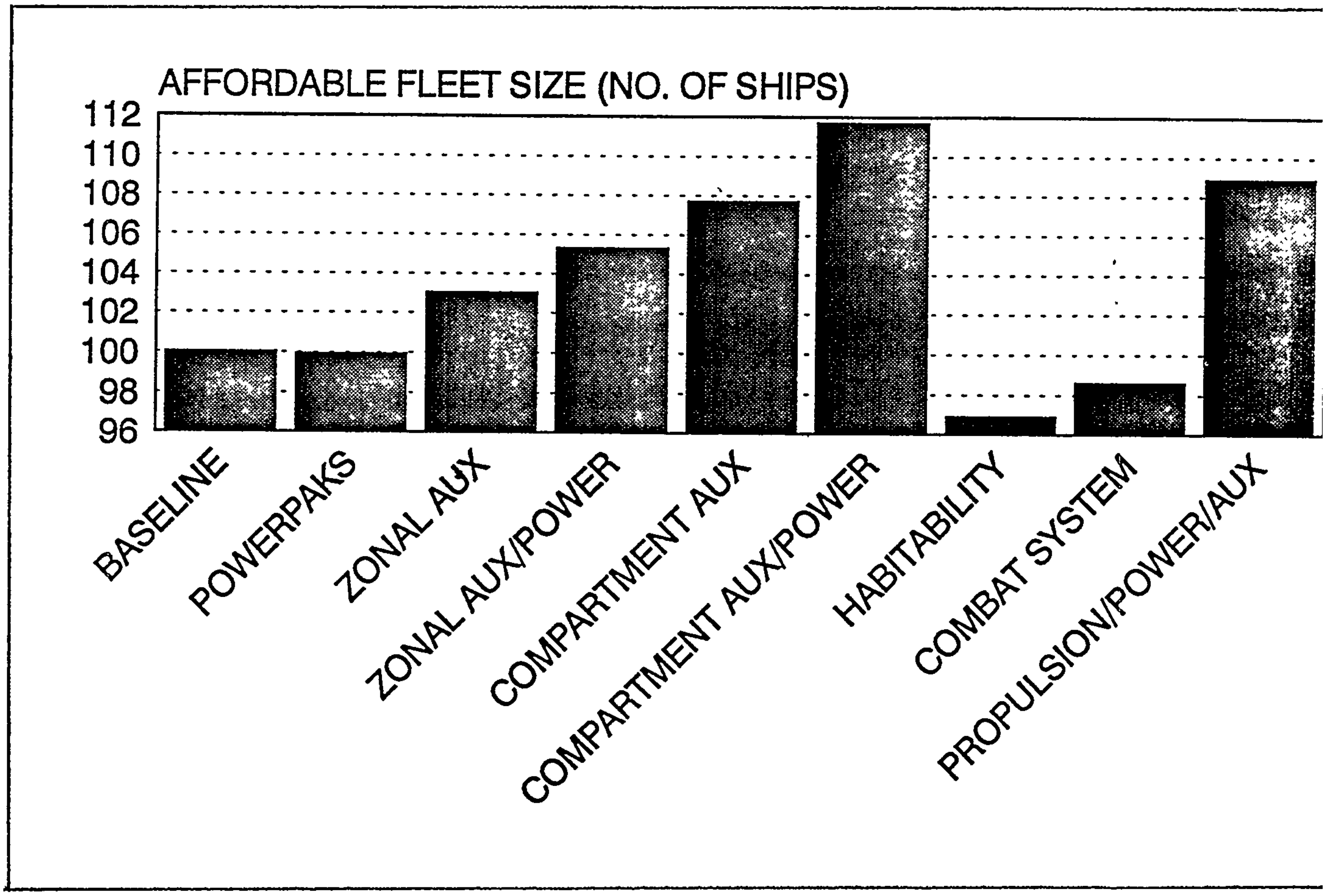


Figure 10. Affordable Fleet Size for Different Type Modules

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Implementation of HSLA-100 Steel in Aircraft Carrier Construction - CVN 74

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ABSTRACT

High Strength Low Alloy (HSLA)-lW steel was developed to be less sensitive to hydrogen embrittlement than High Yield (HY)-1OO steel. The primary benefits sought through the use of this new steel were savings in energy, labor, and scheduling that would result from reduced preheat for welding.

This paper reviews the overall efforts required to implement the use of HSLA-1OO steel during CVN 74 aircraft carrier construction. It discusses the engineering and design effort required to incorporate a new material on a vessel midway through construction. Also included is a discussion of the development of an implementation plan which ensures successful welding procedure qualification, production welding, and inspection of HSLA-1OO welds.

Results confirm that HSLA-1OO steel can be successfully substituted for HY-1OO steel in a shipyard environment and significant benefits can be realized from reduced welding preheat. Also, key elements of future applications of HSLA-1OO are presented.

NOMENCLATURE

CVN	(Aircraft) Carrier Vessel Nuclear
CVN 73	*USS George Washington*
CVN 74	*USS John C. Stennis*
CVN 75	*USS United States*
CVN 76	Proposed New Aircraft Carrier
NAVSEA	Naval Sea Systems Command
HY	High Yield Strength Steel
HSLA	High Strength Low Alloy Steel
SAW	Submerged Arc Welding
GMAW	Gas Metal Arc (MIG) Welding-Spray Transfer
GMAW-P	Gas Metal Arc Welding-Pulsed Transfer
SMAW	Shielded Metal Arc (Stick) Welding
MT	Magnetic Particle Inspection
VT	Visual Inspection
HSS	High Strength Steel (351.7 MPa, 51 KSI Yield Strength)
0ss	Ordinary Strength Steel (234.5 MPa, 34 KSI Yield Strength)
FCAW	Flux Cored Arc Welding

INTRODUCTION

In 1985 the U.S. Navy initiated a program to develop a High Strength Low Alloy (HSLA-1OO) steel to replace High Yield (HY-1OO) steel for ship construction. The program was based on the successful development of HSLA-80 steel as a substitute for HY-80 steel which resulted in cost savings due to reduced preheat requirements for welding. The goal of the program was to develop a steel which met or exceeded the strength and toughness of HY-1OO steel (l). This new steel would be welded using the same consumables and processes as used in the welding of HY-1OO, but with reduced 15.6°C (60'F) preheat. This is much lower than the required minimum preheat for welding HY-1OO, which varies from 51.7ºC (125°F) to 93.3°C (200°F), depending on thickness and the welding process used.

In 1987, Naval Sea Systems Command (NAVSEA) tasked Newport News Shipbuilding to evaluate the weldability of HSLA-1OO steel under various preheat conditions. The results of the weldability evaluation demonstrated that HSLA-1OO steels could be welded together at up to 25.4 mm (1.0 in.) thickness at 15.6°C (60°F) minimum preheat, with the same processes and consumables being used for HY-1OO steels (2). It should be noted that the aircraft carrier design criterion allows the use of undermatched strength consumables (MIL-1OOS and MIL-l 1018) for welding 689.7 MPa (100 KSI) yield steel. The cost of HSLA-1OO steel at the time of the study was slightly more than HY-1OO steel. Therefore, the major cost savings resulted from reduced preheat requirements for

welding. It was determined that about half of the approximate 19,800 metric tons (18,000 long tons) of HY-1OO steel on an aircraft carrier is 25.4 mm (1.0 in.) and less in thickness.

In March of 1989 NAVSEA completed their testing and evaluation phase. At this time a letter of certification was provided indicating that HSLA-1OO was a qualified substitute for HY-1OO steel in CVN construction and could be directly substituted with the following limitations

1. Hull structural plating applications up to and including 102 mm (4 in.) thick were allowed,

2. All crack arrest structure was prohibited from substitution, and

3. All NAVSEA (Nuclear) Code 08 structure was prohibited from substitution.

IMPLEMENTATION

In November 1989, a contract modification for CVN's 74 and 75 was authorized by NAVSEA. This modification allowed the direct substitution of HSLA-100 for HY-1OO to the maximum extent practical within the guidelines previously discussed. The experience base for welding HSLA-1OO steel was too limited to allow the wholesale substitution for all HY-1OO steel in the unrestricted areas of the carriers. Therefore, an implementation plan for its incorporation had to be submitted and approved by NAVSEA. This plan was intended to address welding procedure qualification and create a system to track weld defect rates for HSLA-100 welding as compared to similar HY-1OO welds. Also, the plan required an appropriate corrective action agenda based on quality trends observed during welding.

Plan Development And Approval

When the contract change for HSLA-1OO substitution was authorized, CVN 74 construction was already well under way. Any significant increase in rework and overall cost, or delays to the construction schedule could not be tolerated therefore, close scrutiny of details, and a prudent approach were necessary. The overall construction scheme was already laid out. Most of the drawings were nearly complete, and a large quantity of steel had already been ordered. Many of the lower hull units were fabricated, welded and ready to be erected. However, a limited window of opportunity did exist that would allow a significant substitution of HSLA-1OO in areas where HY-1OO had not yet been ordered, or where purchase orders could still be modified.

The implementation plan was approved by NAVSEA in July 1990. The plan contained the following key elements:

1. Tonnage, thickness, and location of HSLA-1OO steel ordered for the implementation phase;

2. Welding procedure and welder performance qualification details;

3. Nondestructive test criteria for the initial phase of work

4. A system for tracking HSLA-1OO weld defect rates compared to HY-1OO welding; and

5. A corrective action agenda in the event higher defect rates occurred.

The initial application material thickness had to be 25.4 mm (1.0 in.) thick or less.

Approximately 770 metric tons (700 long tons) of HSLA-1OO steel plate were earmarked for the initial hull structural application. About 440 metric tons(400 long tons) of this material was 25.4 mm (1.0 in.) thick, and the remainder was 22.2 mm (0.875 in.) thick.

Upon. successful completion of the implementation effort, welding of HSLA-1OO steel greater than 25.4 mm (1.0 in.) in thickness with reduced preheat would be permitted, providing that supporting welding procedure qualification data could be developed.

Welding Procedure Qualification

The criteria for new construction CVN weld`ing procedure and welder performance qualification is found in MIL-STD-248C (3). Since HSLA-1OO steel was not addressed in this document, supplemental qualification provisions were developed and addressed in the implementation plan for HSLA-1OO steel.

Qualification test requirements were patterned after those for HY-1OO, since the same welding

consumables are used. There were, however, two key elements that dlffered Procedure qualification tests had to be conducted on weldments produced with the reduced preheat temperature intended for the procedure. In addition, welding procedure maximum material thickness was limited to that used for the actual test weldment, when reduced preheat was included in the procedure.

There were four categories of welding procedure qualification tests detailed in the plan:

1. Prior tests conducted on HSLA-1OO with reduced preheat developed under the certification program;

2. Prior qualified HSLA-80, HY-80 and HY-1OO teats that Supported high use (152 meters [500 feet] or more of weld length) service provenprocedures (normally coupled with one or more similarly produced, reduced preheat HSLA-1OO test);

3. Prior qualified tests (including those of dissimilar materials) that support limited use (less than 152 meters [500 feet] of weld length) service proven procedures; and

4. Additional planned procedure qualification work.

In all cases, any deviation from the types of tests required in MIL-STD-248C for HY-1OO welding was required to be identified in the request for NAVSEA approval along with technical rationale to permit the deviation.

Personnel who were qualified to weld HY-1OO, were also considered qualified to weld HSLA-1OO when using the same process and filler material.

Trades Review

Once procedure qualification reports were approved, anew welding procedure was developed and issued for structural trades use. Other quality control procedures were also revised to accommodate working with HSLA-1OO steel.

Prior to the start of production fitting and welding, key personnel from all primary structural trades and support departments participated in a review of the implementation plan. This included a review of significant changes to any procedure requirements, as well as a review of the approach to be used for documentation and collection of information during the first use of each welding process. In the event that any significant unexpected` problem occurred, the shipyard was prepared to address them quickly and thoroughly.

Corrective Action Agenda

During the first weeks of production welding, increased surveillance was performed by quality assurance and' welding engineering personnel. The shipyard was prepared to reevaluate the use of reduced preheat at the first sign of any negative quality trend. The contingency plan was to use normal HY-1OO welding requirements until a specific cause, and necessary corrective action could be determined.

Application Of Welding Process

Shop construction began in March 1991 with main deck panels being welded together using butt joints (Figure 1). The typical joint design for these welds is shown in Figure 2. The temperature in the

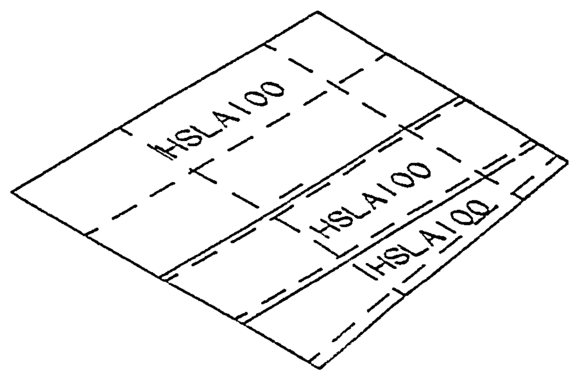
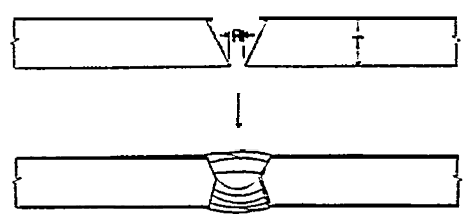


Figure 1 Example of an HSLA-1OO deck panel. Dashed lines indicate backup structure locations



T generally = 25.4 mm (1.00 in.) or less
= 45 Degrees minimum
R generally = 1.6-3.2 mm (0.062-0.125 in.)

Figure 2 Typical joint design for HSLA-1OO butt welds using SAW

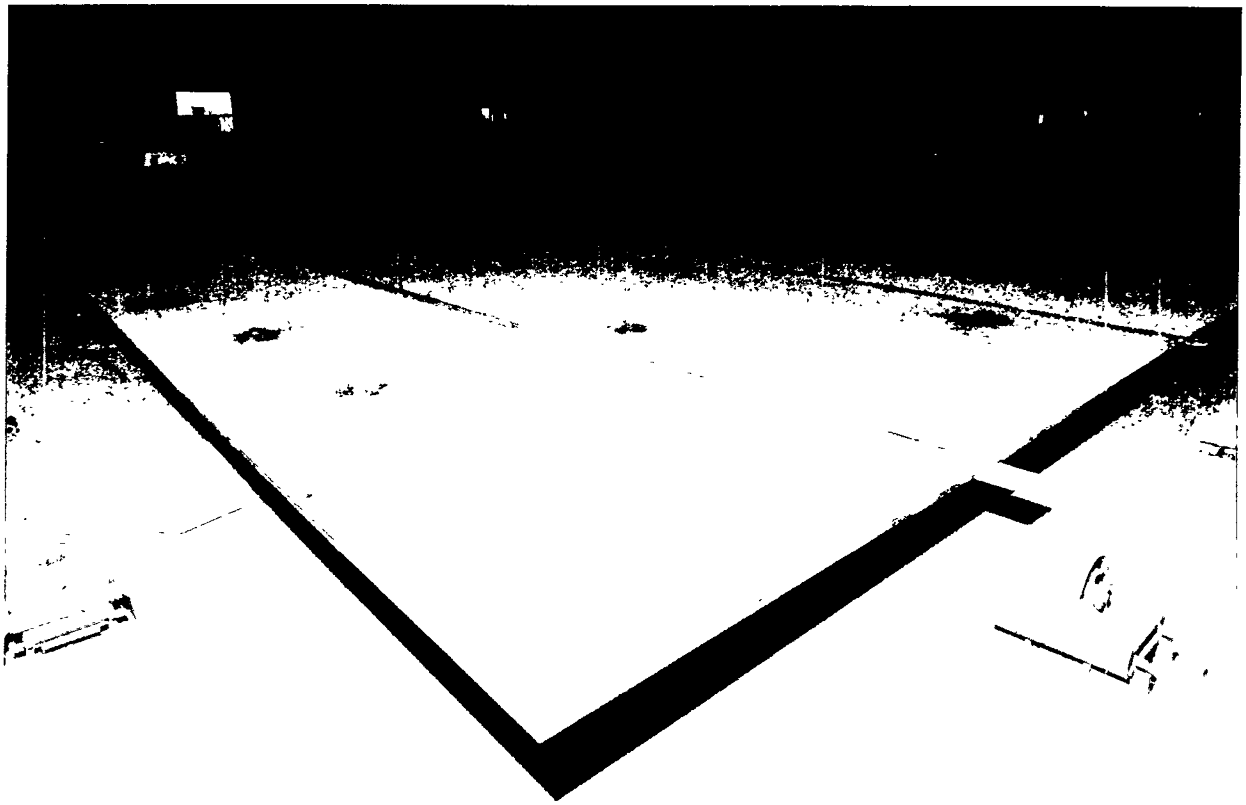


Figure 3 CVN 74 HSLA-100 deck panel after submerged arc welding

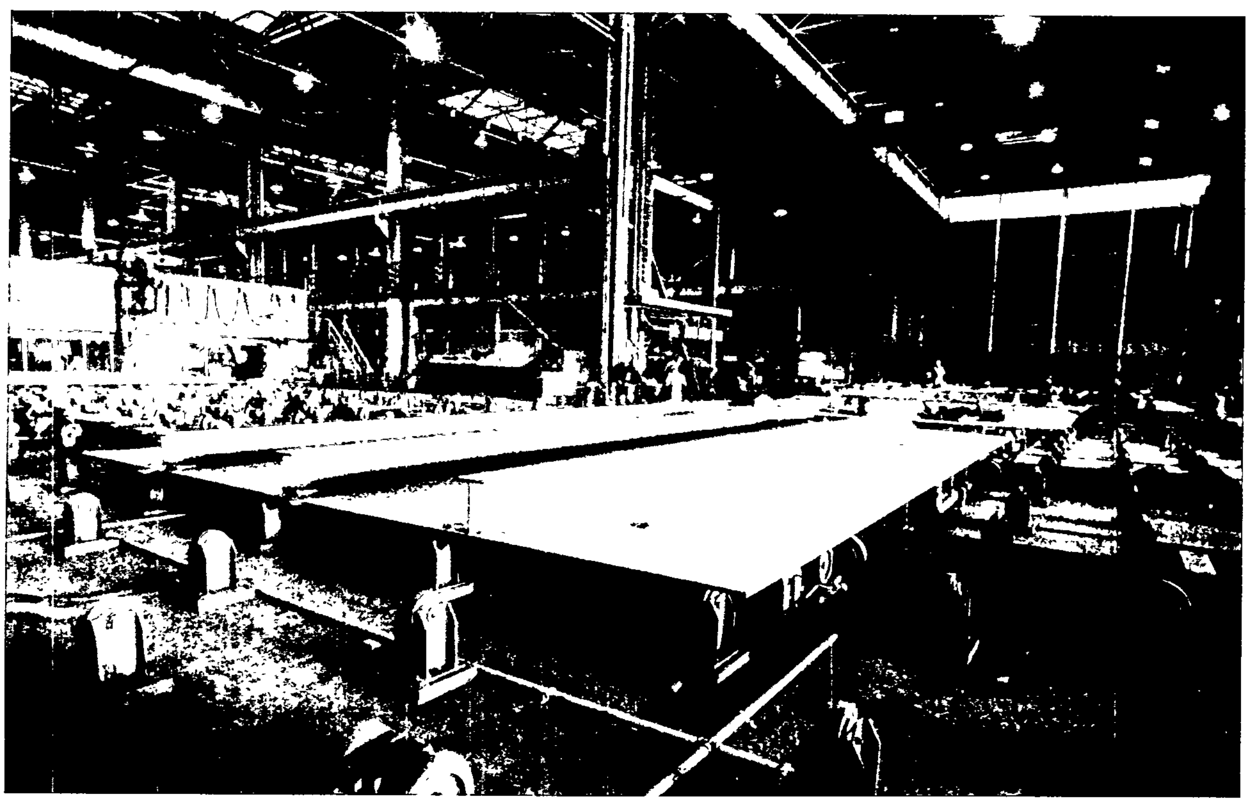


Figure 4 CVN 74 HSLA-100 deck panel with stiffeners attached

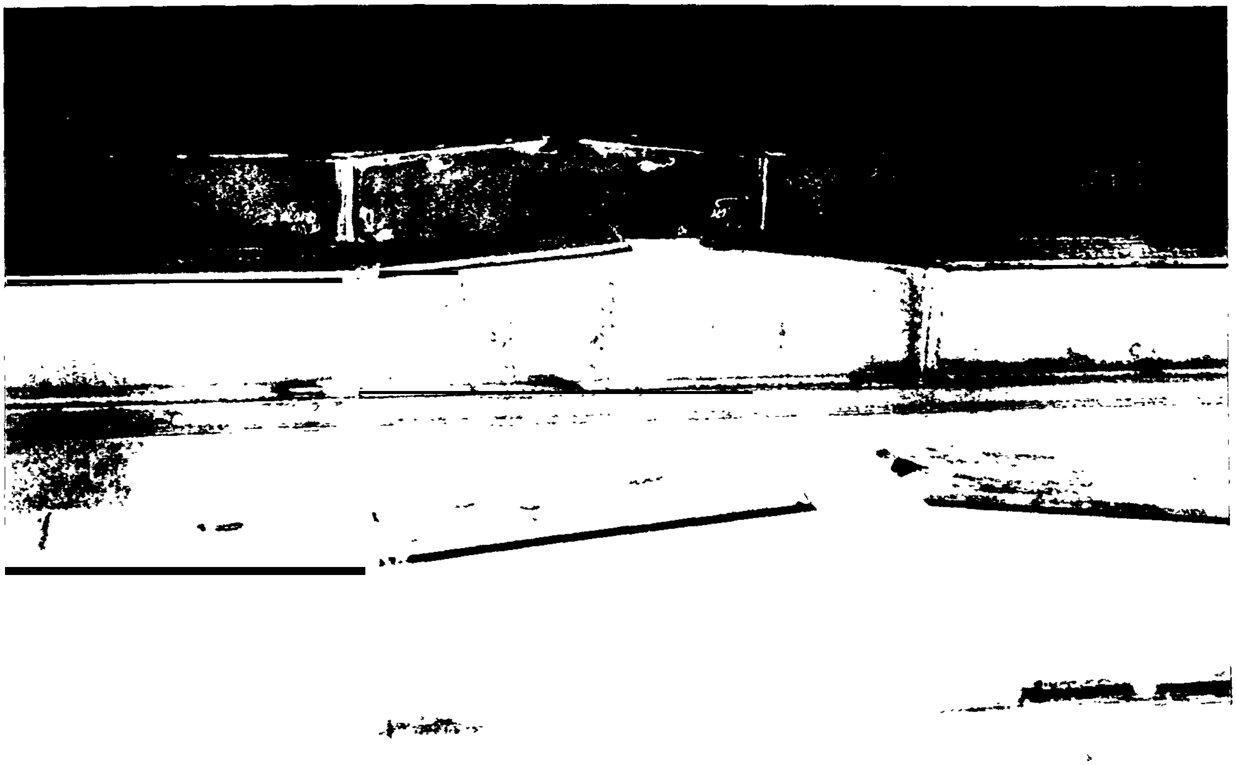


Figure 5 HSLA-1OO deck panel with stiffeners before transverse structure is attached

shop was between 18 & 27°C (65-80°F), so no applied preheating was required. Panels (usually consisting of three or four deck plates) were welded on the first side with twin wire SAW. After the first side was completed, the panels were turned over and the welds were backgouged. Root magnetic particle inspection (MT) was conducted, then the second side of the welds was completed with twin wire SAW. After the HSLA-100 deck panels were completed, they moved further up the panel line to have HSS or 0SS back-up structure attached (Figure 3). Much of the stiffener structure was welded with a dual head SAW gantry system. Figures 4 and 5 show *a* panel assembly after longitudinal stiffeners have been welded. Many of the deck assemblies also had transverse structure added, which involved considerable semiautomatic welding, such as GMAW or FCAW (Figure 6). Some deck panel assemblies were heavily stiffened, which increased the level of required restraint for fitting and welding (Figure 7). If weld cracking problems were to cccur, these more complex assemblies would most likely have shown indications. Once the welding and inspection was complete, units were transported to a platen area with heavy lift capability for "superlift" assembly.

As previously discussed, several different welding processes were used during the initial stages of construction. However, SAW was the primary process used for welding HSLA-1OO plate together. During the superlift assembly and ship assembly stages, overhead GMAW-P was used extensively to weld the bottom side of the deck welds. Table I shows typical processes, consumable, and welding positions used during 1991 and 1992 for joining HSLA-1OO. Table II lists the established preheat and interpass temperature limits for

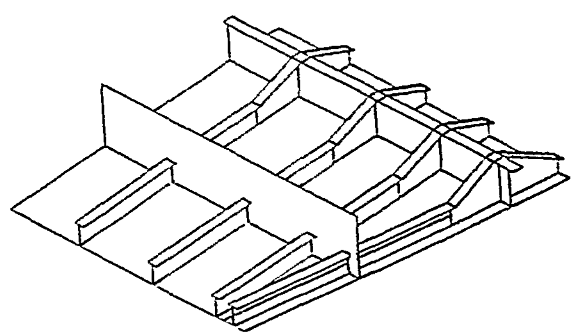


Figure *6* HSLA-1OO deck assembly design with Longitudinal and transverse backup structure

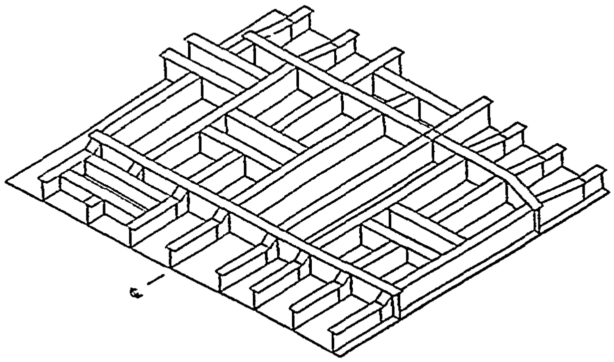


Figure 7 Heavily stiffened HSLA-1OO deck panel design

the processes. Heat input limits for the application of the processes are the same as those qualified for HY-100 welding.

Inspection Processes and Data Analysis

Visual Inspection (VT) was required for all welds during and after welding. In addition, 100% MT was required for all butt welds in HSM-100. MT inspection was usually performed within one to eightweeks after welding, with an average of about three weeks after welding.

Weld inspection data from each HSLA-100 unit assembly on CVN 74 was compared with data from the same unit on CVN 73, where HY-l was used. Periodic quality assurance reports were used to track inspection results for comparison of HSLA-1OO with HY-1OO welding.

Non Destructive Test Results

Initally, to support the implementation plan, 27 deck subassembly units were fabricated, welded, VT'd and MT'd in the shop. The total HSLA-1OO weight for these 27 units was 836 metric tons (759 long tons). This included 403 metric tons (366 long tons) of 22.2 mm (O. 875 in.) HSLA-100 plate and 433 metric tons (393 long tons) of 25.4 mm (1.0 in.) HSLA-1OO plate. A total of 423,000 mm (16,656 in.) of butt weld in the 22.2 mm (0.875 in.) HSLA-1OO plate was inspected with a total of 203 mm (8 in.) of repair weld being required in two locations. Neither repair area contained

Process	Electrode Type	Flux Type	Welding Position
SAW	MIL-100s-l	MIL-1OOS-1F	FLAT
GMAW	MIL-1OOS-1	NA	FLAT OR HORZ.
GMAW-P	MIL-1OOS-1	NA	ALL
SMAW	MIL-11018	NA	ALL

Table I Typical welding processes, filler materials and welding positions for HSLA-1OO

HSLA-1OO Thickness mm (in)	Minimum Preheat & Interpass Temperature: °C (°F) 1/		
	SMAW	GMAW/GMAW-P	SAW
≤25.4 (1.00)	15.6 (60)	15.6 (60)	15.6 (60)
>25.4 (1.00) To <31.7 (1.25)	51.7 (125)	51.7 (125)	51.7 (125)
31.7 (1.25) To 69.8 (2.75)	93.3 (200)	65.6 (150)	65.6 (150)
Over 69.8 (2.75)	93.3 (200)	93.3 (200)	93.3 (200)

1/ Maximum preheat and interpass temperature is 149°C (300°F)

Table II Established preheat and interpass temperature limits for welding HSLA-1OO to itself

any transverse cracks or hydrogen related defects. A total of 420 meters (16,524 in.) of butt weld in the 25.4mm (1.0 in.) HSLA-1OO plate was inspected with no repairs required. Records for the same HY-1OO units on CVN 73 were examined 813 mm (32 in.) of rejectable indications were recorded for 850,000 mm (33,468 in.) welded.

Since the initial implementation phase of this project, those same 27 deck units on CVN 74 were joined into larger subassemblies, and later were set into place on the ship, and welded and inspected. Total inspection for HSLA-100 shop and shipboard welding operations amounted to approximately 1,270,000 mm (50,000 in.) of weld, with 813 mm (32 in.) requiring weld repair (less than 1/10 of 1%). The defects in the later cases initially appeared as transverse cracks on the weld surface, but upon excavation were found to originate from lack of fusion and slag defects. These defects were caused by poor access to the lower side of the weld joints in way of stiffener crossovers.

Overall, the initial phase of the program was considered a complete success; this led to the next phase incorporating additional HSLA-1OO in the ship.

ADDITIONAL HSLA-1OO ON CVN 74

Since it was demonstrated that HSLA-1OO material could be satisfactorily welded with reduced preheat in a production environment, the shipyard began ordering additional HSLA-1OO steel (including thicknesses greater than one inch) for the substitution of HY-80 and HY-104 on CVN 74 and CVN 75. Since CVN 74 was already midway through construction, a special engineering/design effort was required to incorporate this additional HSLA-l material. The following step-by-step plan was used to identify and purchase all of the additional HSLA-1OO steel used on CVN 74:

1. A cut-off date for material required-in-yard was established for purchase orders. Orders scheduled to be placed after the established cut-off date became candidates for HSLA-1OO.

2. Purchase orders identified in Step (1) were reviewed to insure that HY-80 and HY-1OO material had not been received early or was not in the process of being rolled early. In this effort, the shipyard's purchasing department "Plate Track" computer program was used to identify in-process material.

3. All drawings that detailed the HY-80 and HY-1OO material that was to be ordered via the candidate purchase orders were reviewed.

4. Engineering personnel then determined if there were large enough areas of HY-80/100 on these drawings to make the substitution worthwhile. It was not beneficial to substitute HSLA-1OO if it was mixed with strakes of HY-80 or HY-1OO, since applied preheat is usually required when welding HSLA-1OO steel to HY steels.

5. Once steps (1) through (4) were accomplished, existing purchase orders were modified and new purchase orders were created for the HSLA-1OO that could be substituted. Detail drawings were then revised to reflect where the HSLA-1OO would be used.

Approximately 1270 metric tons (1250 long tons) of HSLA-1OO are being installed on CVN 74. Table III shows a breakdown of tonnage and thickness. The majority of tonnage clearly falls within the limits for reduced preheat: less than or equal to 25.4 mm (1.0 in.) thick. For those areas where the thickness is greater than 25.4 mm (1.0 in.), HY-1OO welding preheats are still being used. This need to preheat results from limitations of the welding consumables, not the base material. Less hydrogen sensitive consumables are under development to allow reduced preheat for welding thicker HSLA-1OO material.

THICKNESS mm (in)	TONNAGE metric (long)
15.9 (0.625)	-272 (-268)
22.2 (0.875)	-381 (-375)
25.4 (1.00)	-481 (-473)
>25.4 (>1.00)	-46 (-45)
MISC	-90 (-89)
TOTAL	-1270 (-1250)

Table III Use of HSLA-1OO on CVN 74

HSLA-1OO ADVANTAGES

There are many cost factors to consider when evaluating the use of HSLA-1OO steel in lieu of HY-100, such as equipment, equipment maintenance, set-up labor, energy, schedule impact, automation hindrance, delays (preheat/interpass), welder operator factor, and clean-up labor. Some of these factors, such as equipment and labor, have easily assignable costs. However, for other intangible benefit factors, such as enhanced automation and increased welder operator factor, it is difficult to determine the exact cost benefit.

For preheat cost saving considerations, most areas where aircraft carrier units are constructed are enclosed and ambient temperature is normally above 15.6°C (60°F). For HSLA-1OO with a thickness of 25.4 nun (1.0 in.) or less in these areas, application of welding preheat is normally no longer required. Heating equipment capital, maintenance, set-up labor, energy and clean-up labor costs, which could be assigned on a per ton or per length of weld basis, in this case would be no longer applicable. As the thickness increases the amount of heating equipment per given length of weld may increase as well. If, for example, heater bars are typically used, then it would be appropriate to determine the number of bars of a given size normally used per equivalent ton of HY-1OO structure to develop the associated cost savings.

The schedule impact of using HY-1OO is being evaluated. Delays can be incurred by the application and removal of heating equipment, and waiting for welds to reach proper preheat temperature, or to cool down to the proper interpass temperature. The total cost of facilities and other equipment used but not contributing to deposited weld may be difficult to determine so it would be appropriate to assign a percentage value for delay time cost savings. Also, automated process improvements and higher productivity may result from the elimination of preheat. However, if hard to quantify, productivity improvements could be estimated with a percentage value as well to arrive at a cost per ton savings figure. Together, these individual cost factors are a good baseline for estimating preheat cost savings.

Considering base material expense, initially the cost of HSLA-1OO steel plate was expected to be substantially higher than HY-1OO, due to higher alloy content. But shortly after the implementation program was under way, the lean chemistry grade of HSLA-1OO was certified for thicknesses of 25.4 mm (1.0 in.) and less. This lean chemistry formula led to reduced costs and, along with reduced preheat, increased the potential cost savings for the substitution. Also, the price of both lean and rich chemistry HSLA-1OO steel has been reduced since initial purchase. In January, 1990, the average cost difference of HSLA-1OO steel plate over HY-1OO plate was $142.50 per metric ton. In March, 1993, the average difference in cost was just $20.00 per metric ton.

The exact total cost difference in dollars per ton between HSLA-l00 and HY-1OO construction varies. It depends largely on the complexity of an assembly, and the extent of attachment welds no longer requiring preheat. Energy and labor costs are the two major factors. Rough order of magnitude savings estimates range anywhere from $500 to $3000 per metric ton before any applicable implementation costs are considered.

FURTHER APPLICATIONS

Once initial welding of HSLA-1OO with reduced preheat was satisfactorily proven on CVN 74, planning began immediately for widespread substitution of HSLA-1OO on CVN 75. As of March 1993, a total of about 15,420 metric tons (14,000 long tons) of HSLA-1OO is scheduled to be substituted on CVN 75. An even greater use of HSLA-100 is planned for CVN 76.

Welding procedure qualification tests with new lower diffusible hydrogen consumables are providing promising results. The primary objective is to increase the thickness at which 15.6°C (60°F) preheat can be used to produce satisfactory welds in a worst case environment under conditions of high restraint.

CONCLUSION

With reduced defense budgets and ever increasing pressure to cut costs, the use of HSLA-100 steel on Naval combatant ships is a significant step in the right direction.

Cooperation and thorough planning by the Navy, steel suppliers (Bethlehem Steel, Lukens Steel and United States Steel) and the shipbuilder have resulted in a successful implementation program of HSLA-1OO steel on CVN 74 with reduced welding preheat.

Some suppliers of welding consumables (ESAB/L-TEC and Lincoln Electric company) are currently concentrating on the development of new filler

materials that could lead to the welding of thicker HSLA-1OO steel with reduced preheat. Their ability to provide the very low diffusible hydrogen consumables needed for reduced preheat welding is the key element in taking full advantage of this new steel.

REFERENCES

1. Earnest J. Czyryca, "Development, Qualification, and Certification of HSLA-80 and HSLA-1OO Steels for U. S. Navy Ship Construction," PP 553-572, Proceedings - International Conference on the Metallurgy, Welding, and Qualification of Microalloy (HSLA) Steel Weldments. American Welding Society, 1990.

2. D. T. Wallace; "HSLA-1OO Weldability Test for CVN 73 Material Substitution for HY-1OO Steel," Welding Engineering Technical Newport News Shipbuilding, 1989.

3. "Welding and Brazing Procedure and Performance Qualification. MIL-STD-248," Naval Ship Engineering Center U.S.A.

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The Department of the Navy Approach to TQM

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ABSTRACT

The Department of the Navy (DON) has adopted total quality management (TQM) as the principal leadership and management system to achieve mission effectiveness. Adapted for practice by DON personnel, the approach has been called Total Quality Leadership (TQL) in order to emphasize the pivotal role played by leaders. The purpose of this paper is to describe TQL and the approach used for implementation.

The central thesis of the paper is that the change to TQL is transformational in nature. Transformational changes require a planning approach that is sensitive to the systemic effects of organizational changes. **Strategic** change management (SCM) is described as the methodology for achieving this change in the DON. The rationale for SCM is described and the resulting implementation approach is evaluated.

CORNERSTONES AND BASIC CONCEPTS OF TOTAL QUALITY LEADERSHIP

Total QuaIity Leadership is defined as "the application of quantitative methods and the knowledge of people to assess and improve (a) materials and services supplied to DON organizations, (b) all of the significant processes within organizations, and (c) meeting the needs of the end user, now and in the future (l)."

The purpose of this paper is to describe TQL and to indicate how it is being implemented in the Department of the Navy. A brief history of TQL in the DON is described by Walton (2).

The Five Cornerstones of Total Quality Leadership

Definition of total quality leadership. The definition of TQL provides a description of the operations required to practice TQL (application of quantitative methods and knowledge of people to assess and improve), the breadth of the effort (all "significant" processes performed by the organization) and the time horizon (now and in the future).

In practical terms, the practice of TQL requires that managers identify and improve all of the organizational processes that have a significant impact on mission performance. The process orientation usually require that non-management personnel be enlisted to (a) identify how the processes are actually performed, and (b) use their process knowledge in the improvement effort. TQL also requires that objective measurements of process performance be used as the basis for understanding and taking action on processes, as well as evaluating the effects of process changes.

For operational units, clear criteria for mission effectiveness must be developed, as they are surrogates for customer requirements. Organizations serving operational units are to develop their criteria based upon the quality requirements of their customers in the operational units. once the quality criteria are established, the TQL effort

is directed at optimizing organizational performance to achieve these criteria in the most economical way acceptable to their customers.

The Deming philosophy provides the theoretical basis for TQL. Based upon the theory of profound knowledge, it has empirical roots in (a) the mathematical basis for quality improvement, (b) the application of systems theory to quality management, (c) the psychology of teamwork and leadership of change, and (d) the use of the scientific method as the basis for determining the causes and effects of quality (3).

Department of the Navy implementation approach. Due to the high levels of turnover among military commanders, the approach to implementation takes place in two phases. The first phase consists of establishing continuous quality improvement as the principal management practice in DON organizations. The second phase, usually undertaken by succeeding commanding officers, is establishment of a system for the practice of strategic change management. This latter capability is primarily intended to deal with the systemic changes arising from the impacts of continuous quality improvement. The second part of this paper will deal with this approach in detail.

Management structure for TQL. Each DON organization is to have a steering committee that is responsible for implementation. The steering committee is linked internally to line and staff teams that are specifically chartered to improve all mission-essential processes. The steering committee is also linked externally through the commanding officer to higher levels in the chain of command that (typically) are more responsible for the long term, systemic changes required during the second phase of implementation.

A scientific approach to quality improvement. Quality improvements are undertaken within a data-based systems context. In this approach, the processes important to mission capability are identified, stabilized, and improved using a disciplined procedure based upon the scientific method (4). These planned changes are based upon top-down priorities, coupled with an assessment of the systemic impacts of the improvements. The benefits of this approach are (a) optimal mission performance, and (b) minimal cost.

Basic Concepts of TQL

The meaning of “customer.” The DON is divided into two categories: “providers” (administrative) and “combatant forces” (operational). For the DON as a whole, the operational forces are regarded as the customer of the providers or adminstrative members of the DON. It is the quality requirements of the operational forces that must be known and exceeded by the providers of goods and services. For any given organization within the DON, there are both internal and external customers. Those “internal” are members of a command providing a product or service to others within their command. Those “external” are the recipients of the product or service outside of their command. As was indicated above, the most significant customer, sometimes referred to as the “end user,” is the sailor or marine that provides primary defense (l).

The “extended system.” Quality is judged by the customer, consumer, or end-user of a product or service. That judgment is the response to a quality characteristic produced by a series of service or production processes that can be traced backwards through the producing organization, and into the supply base of the producing organization. This is referred to as the “extended system,”

and is considered the basic unit for continuous quality improvement.

Management's "new" job. Process improvement, based upon measurement and analysis of process variation and the actions required to improve processes through reduced variation, has not historically been the job of management. TQL requires that all leaders and managers use this new approach to quality management, and that it be made a requirement for satisfactory job performance.

Organizational transformation. Process improvement on an organization-wide basis is a fundamental change in the technical system of the organization. Such change inevitably impacts the political and cultural systems of the organization as well, and can not be successful unless all three systems are brought into alignment. It is the optimal performance of this total system that is referred to as organizational transformation.

Strategic change management. The process used to achieve organizational transformation is strategic change management (5). The goal of strategic change management is optimization of mission effectiveness through alignment of the organization's technical, political, and cultural systems. Such alignment is difficult due to the size and complexity of the DON. As a result of this, authority for making changes in the technical subsystem is delegated to the unit level. Changes in the political and cultural subsystems are primarily the responsibility of organizations at higher echelons.

Unit-level implementation. Continuous quality improvement is to be established as an organizational practice by all commanding officers in the Department of the Navy. Impediments to this practice that are beyond the control of a commanding officer are to be addressed through the chain of command. They are addressed at the appropriate level by those in authority using the strategic change management methodology.

Change is managed top-down. Due to the systemic impacts of changes in organization systems, quality improvement efforts are managed top-down. This is done to avoid suboptimization, preserve the chain of command, and avoid the false starts commonly associated with bottom-up efforts. This does not preclude participation by those lower in the organizational structure. Rather, it simply emphasizes the fact that TQL is a management system, not an employee involvement program.

TQL team structure. Continuous quality improvement is largely team based. By definition, extended processes require cross-functional management teams (QMBs). Such teams are more successful for achieving system optimization, and also make more efficient use of resources (time). Improvements within functions (PATs) also require management to ensure efficiency of resources, optimization of improvements, and avoidance of false starts.

Chain of command. Changes in systems and processes, and the attendant expenditure of resources, are managed through the existing chain of command. The TQL team structure provides a horizontal integration of the chain of command that reflects process ownership. No new organizational structures are required for the practice of TQL, as long as authority to act on process improvements is delegated to the process owners working as a team.

Shared leadership. Improvement means change, and change requires

leadership. It is the fundamental responsibility of the commanding officer to develop a capability for the continuous improvement of all mission-essential processes. In order to do this, s/he must develop a "critical mass" of leaders who will lead quality improvement efforts (3).

Process improvement. Processes are improved when they (a) are less variable, (b) increase value to the customer, and (c) contribute to optimization of a system. These requirements cannot be met by problem solving alone, although the solution typically begins that way. Following initial efforts to stabilize process performance, TQL process improvement methodology focuses on identification and removal of the causes of unwanted variation. Such an approach does not depend upon the existence of a problem--but does rely upon a commitment to continuous process improvement (4).

STRATEGIC CHANGE MANAGEMENT AND TRANSFORMATION TO TQL

Strategic change is defined as a change "of great importance within an integrated whole or to a planned effect (6)." The "integrated whole" is the Department of the Navy. The "planned effect" is optimal mission effectiveness achieved through the practice of TQL. This use of "strategic" is quite dissimilar from the military concept of the term. In the context of leadership it simply means an important change in strategy. The new strategy is TQL. Moving from the current management system, where quality is inspection based, to the practice of TQL is a strategic change. It is also transformational.

The nature of transformational change. Transformational change is like metamorphosis--going from caterpillars to butterflies. It is not linear change, it is discontinuous and non-incremental in nature. Metz (7) has described the requirements of such change as:

"A comprehensive, long term horizontally and vertically linked strategy needs to be developed. (It) will have to cover the entire organization with all its systems and procedures, and will need to be incorporated into the overall business strategy. Long term improvements will not be accomplished without *permanent changes in the level of employee involvement;* without *changes in points of authority, responsibility, and decision making;* without *changes in management philosophies, styles, and relations* and without *changes in climate and culture.* " (italics mine).

For an organization as large and complex as the DON, the kind of change described by Metz must be planned and managed to take into account the diversity of organizational cultures that make it up. At a minimum, the various cultures include the three Navy communities, (air, surface, submarine) the Marine Corps, the civil service, and, perhaps, women in the DON.

Metz observed that most efforts at implementing transformational change go through three evolutionary steps. He refers to these as Type I, II, and III, with the third type being transformational. The extent of change, moving from Type I to III, does not appear to be linear. Rather, it seems exponential, especially as it applies to (a) teamwork and (b) management and employee involvement, i.e., the "people" dimension.

Deming (3) has asserted that there is clear evidence that much of the western world is in an impending crisis, and that an organization must transform more rapidly than the evolution described by Metz. He points out that most efforts at programmatic change (Metz's Type I--as typified by quality circles) result in little more than "false starts."

What emerges from the thinking of these and other writers (8) & (9) is that all three major organizational systems that must be changed: the technical. the cultural. and the political. In addition, what is needed is *planned* change, but not in the formal sense

typically associated with business planning. Rather, what is required is *an adaptive strategy for planning and implementing change* that reflects the variations in size, complexity, and cultures of the Department of the Navy.

A Theory of Transformational Change

Rational approaches to transformational change have been described in the area of management known as Organization Development (OD). OD is an emerging discipline directed at helping organizations manage such change more effectively (10). Of particular relevance to the DON is the OD methodology known as strategic change management (5). *Strategic change management (SCM) is a scientific methodology for achieving transformational change based upon the systems theory of organizations.* Strategic change management is the "adaptive strategy for planning and implementing change" mentioned above, and the answer to Metz's entreaty for a comprehensive, long term strategy incorporated into the overall business strategy, also mentioned.

The relevance of SCM is derived from the fact that this methodology pays specific attention to the three primary systems of organizations: technical, political, and cultural, that have evolved to deal with three basic problems of organizational life.

The first problem is that of productivity. That is, in the present era of budget cuts and downsizing, the technical system (methods, manpower, machines, material) must be rearranged in the most efficient manner. The method for doing this is process improvement, beginning with simplification and elimination of waste, and continuing with iterative improvements based upon reduction of variation (4).

The second problem has to do with the distribution of decision-making authority, particularly as it applies to resources. This is related to how power is distributed in the organization, i.e., the political system. Effective transformation to TQL makes necessary the reallocation of authority in order to improve processes. The sheer magnitude of changes involved in process improvement will require that decision-making be pushed to the lowest level possible. This will change the knowledge, skill, and ability levels of many jobs, and the systems of compensation and reward that support those jobs.

The third problem has to do with "glue" that holds organizations together, the cultural system. In this time of drastic change, top leaders must decide the content of the organization's culture: which values are to be shared and taught, and what beliefs and actions are required of the members of the organization to support the values. Having decided these, top leaders must communicate them in a memorable and believable fashion which will not be quickly dismissed as "just another program." The value of central concern to TQL is the quality of products and services.

SCM involves keeping the three systems balanced or aligned. According to the theory, *alignment of these systems in the context of continuous quality improvement leads to optimal organizational performance.* Tichy presents three basic sets of *managerial* tools for aligning the three systems:

(a) the mission and strategy of the organization;
(b) its structure, including administrative procedures, and
(c) human resource management practices. These tools can be used to modify or adjust any or all of the three systems.

The Strategic Change Management Matrix

Figure 1 depicts the SCM concept. The entries in the matrix represent the strategies undertaken to establish or maintain alignment of the three organizational systems. The matrix will be briefly described here (specific illustrations depend upon organizational context--this is what was meant by "adaptive" earlier). The remainder of this section of the paper will describe some strategies associated with the technical row and the human resource management column of the matrix. No attempt will be made to describe the details of the DON approach in a single matrix.

However, general applications for the DON will be described in a subsequent paper. (Those familiar with Deming's 14 obligations of management could readily put those strategies in this matrix).

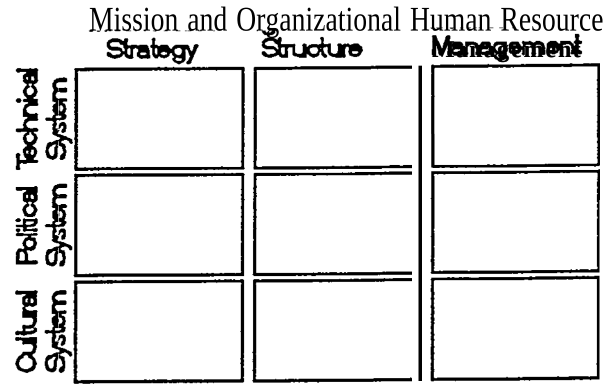

Fig. 1 A Matrix of Actions Required to Apply Strategic Change Tools to Organizational Systems

The technical system (the first row in the matrix) is concerned with reducing or more effectively organizing the organization's personnel, technology, material, and financial resources to produce a desired outcome--improved product or service quality, in this case. The first managerial tool used to adjust the technical system involves the mission and strategy of the organization. The mission fits the organization's resources to the environment. It is defined first by assessing the environmental threats and opportunities facing the organization. Then, the organization's strengths and weaknesses are identified. A mission is chosen which best links the organization's strengths to environmental opportunities. Finally, a strategy is worked out for how the organization's resources will fit together to achieve the mission.

The second managerial tool which can be applied to the technical system involves organizational structure. Given the process improvement focus of TQL, the objective is to structure management teams to correspond with the flow of processes. If the organization is functionally aligned, this will result in a matrix--maintaining the chain of command while incorporating cross-functional teams.

The human resource management system is the third tool for adjusting the technical system. It involves fitting people into jobs or roles and devising methods for measuring and improving their performance. Prominent among these roles are team leader and team member. Principal actions here involve training for new role requirements, as well as career planning for longer term job progression in team leadership.

Human resource management (third column in the matrix) can also be discussed as a tool that applies across the technical, political, and cultural systems. As indicated above, it concerns fitting people to jobs, specifying and measuring performances, and staffing and development when applied to the technical system. These tasks are concerned with linking the organization's social resources to its technical resources so the production system can operate effectively.

When applied to the political system, human resource management is more involved with social power than simply with production. It includes succession politics--who gets ahead and how they do it. For example, in an aviation depot, the path to power might indirectly through engineering rather through the production department. There are also political human resource issues related to reward and appraisal systems. Organizations must decide who gets what rewards and how, they must choose by whom and by what criteria employees are appraised. These issues frequently pose difficult dilemmas because the political aspects of human resource management can conflict with the technical aspects.

The application of human resource management to the cultural system is more concerned with organizational values than with social power or production efficiency. Major attention is directed toward selecting, developing, and rewarding people to shape and reinforce a particular culture. In the DON, an emphasis on culture could result in attempts to select and retain members whose personal values fit well with the Navy or Marine Corps of the future. Alternatively, attempts to socialize or redevelop appropriate

values can be effected through training or changes in the appraisal and reward systems.

In summary, the essence of the SCM approach to transformation is through application of three change tools to each of the three organizational subsystems. This would generate as many as nine change strategies for improvement of the organization. The particular strategies employed depend upon an assessment of the internal and external environments of the organization. In using the matrix, leaders must recognize that the organization (at whatever level) is not static--and the appropriate strategies in the matrix require continual attention and adjustment. Therefore, transformation must be viewed as an ongoing process rather than an end state.

Adapting Strategic Change Management **to the** DON.

Top leadership must apply three steps to change an organization from its present condition to one that is transformed. First, envision the future state of the organization with its loosely coupled technical, political, and cultural systems aligned (for total quality). Second, uncouple the three systems and seek to change each separately. (For practical purposes "uncoupling" means that leaders and managers are given additional time and resources to begin process improvements.) Third, recouple the three improved systems. Recoupling would occur when the practice of process improvement becomes an integral part of a manager's job. An example of recoupling on the power dimension is that changes in appraisal and award systems would become connected with process improvement activities.

These three steps have been adapted as an approach for implementation of the "total quality" concept in the Department of the Navy (11). However, due to the size, complexity, and variation in organizational cultures in the DON, it has not been possible to treat it as a single organization with regard to the three steps to change. In order to accommodate these issues, authority for transformational changes was delegated as follows:

(a) responsibility for process improvement (mainly changes in the technical system) was delegated to the individual command

(b) changes in political and cultural systems that have no impact outside the individual command are to be made by the individual command, and

(c) responsibility for changes in political and cultural systems that have systemic impacts outside the individual command must be surfaced through the chain of command.

The practical effects of the rules of delegation are:

(a) for most DON organizations, developing a vision is largely restricted to their understanding of the effects of process improvement on organizational functioning (12),

(b) uncoupling and improving the technical system can take place at all levels in the chain of command, but uncoupling and improving of the political and cultural systems is largely a responsibility of headquarters-level organizations (13) and

(c) redesign and recoupling of the political and cultural systems are primarily a headquarters responsibility (14).

Implementation in Two Phases. Considering the above, transformation to TQL involves two sets of activities. The first--and primary for most DON organizations--is to begin the practice of continuous quality improvement through redesign of the technical system (i.e., all significant organizational processes) in every DON organization. The second--and more typical of headquarters organizations--is transformation of the political and cultural systems to support continuous quality improvement.

Figure 2 describes, for a hypothetical organization, how these two sets of activities might take place. The diagram presents a block of time representing the total time spent by management on quality improvement. The vertical axis represents the levels of management in an organization. The horizontal axis presents time intervals--which are not necessarily fixed--allowing flexibility for the myriad of DON organizations.

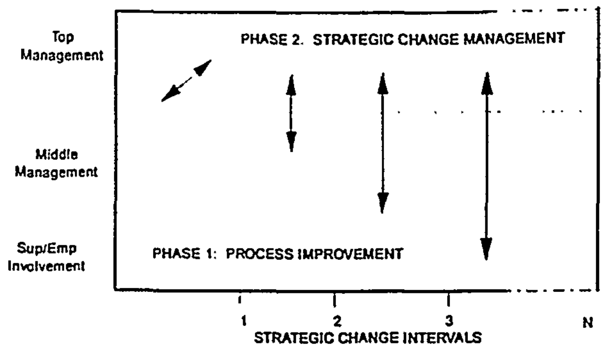

Fig 2 The DON Two-Phase Approach to Implementing TQL

The diagram indicates that, initially at least, most time is spent on establishing and practicing continuous process improvement, i.e., establishing the ability to make continuous changes in the technical system. Then, as time goes by, top management attention becomes more focused on managing changes in the political and cultural systems. The bi-directional arrows are to indicate that these changes interact systemically.

Experience has shown that it is important for top management to be involved with Phase 1 of implementation. This is important for two reasons: (a) continuous process improvement requires visible and involved leadership and elements of it cannot be delegated, and (b) top management may not be able to form a vision of the political and cultural impacts of TQL if they do not participate in the practice of process improvement. Given these two facts, it would not be appropriate for top management to delegate Phase 1 activities and simply concentrate on SCM.

Implementation and Management is Top-Down. There are several reasons for why the technical system changes should come first and why changes in the political and cultural systems are designed and implemented top-down within the DON. Changes in the technical system are undertaken initially because of the need to increase the efficiency and effectiveness of naval organizations. This has been due to the massive reductions in defense funding as a result of the federal deficit and reduction of the Soviet threat. Process improvement was viewed as a way to maintain the integrity of the DON - mission while simultaneously reducing the cost of operations.

Changing the technical system also "triggers" changes in the political and cultural systems. In other words, process improvements require modification in points of authority for decision making, and involves more employee involvement than currently exists. If these changes are consistently reinforced by the political system, and appropriate rewards and appraisal mechanisms are put into place, the culture of the organization will also begin to change.

Because effective implementation requires that power be shared, it makes sense that the overall effort must be top-down. Changes in power, as well as changes required in the appraisal and rewards systems, can't realistically *come* from lower in the organization (without revolution). As a result, planning and execution of changes in power and culture are a top management responsibility. (Changes in politics and culture need not necessarily be driven by process improvement, but Total Quality Leadership cannot be fully achieved without realignment of the political and cultural systems.)

Several other reasons for a top-down approach are important for consideration.

(a) People at the top are in a better position to ensure that the various process improvement efforts are orchestrated in such a way as to avoid suboptimization. That is to say, they are in organizational positions that can ensure that the efforts complement one another in support of organizational goals.

(b) It is more likely that the improvements undertaken will be important to the mission of the organization if they are directed top-down.

(c) The procedures for process improvement are fundamentally the same whether the process is one of great importance to the organization or one that is relatively inconsequential. Sometimes, if not directed otherwise, managers will undertake these latter efforts in order to minimize risk under the assumption that an unimportant process is actually less risky. But, that depends on how you define failure. If it takes 3,000 man-hours of effort to improve a process that is unrelated to the mission, then you have probably wasted 3,000 hours.

(d) A top-down approach fosters a sense of process ownership. In bureaucratic organizations there is an overwhelming tendency to want to "kick it upstairs" when the need for change is discovered (15). This appears to be due to a fear of accountability, rather than a need to coordinate action on a change. However, the effectiveness of change is greatly dependent on the degree of ownership of what is being changed (16) & (17). In TQL, ownership is determined *a priori* as a part of the team chartering process. In other words, when management decides what process they want to change, they use a deployment flow chart to determine membership on the teams. Through the same process, authority to act is delegated. Although it might be argued that a sense of ownership could better be established using a "bottom-up" approach, the abysmal failure of quality circles in the Department of Defense argues against that approach (18).

The DON Hierarchy and Responsibility for Transformation. The ability to make permanent changes to the political and cultural systems resides high in the DON chain of command. For that reason, transformational activities related to these systems should be addressed there. Thus, the proportion of time spent on changes to the political and cultural systems in headquarters organizations should be greater than, say, in an operational unit such as a submarine. Conversely, almost all of the time spent on quality improvement in a submarine would be focused on the continuous, day-to-day improvement of processes. So, if Figure 2 was drawn for a submarine, most of the temporal space would consist of Phase 1. For a HQS policy organization, the opposite might be true.

Due to the above, only higher echelon organizations in the DON should be concerned with strategic change management. The other 95%+ organizations should be almost wholly concerned with identifying and improving the processes that are important to the mission of the organization. There could easily be hundreds of such processes, so each organization will have to perform a prioritization analysis and apply their resources accordingly. Eventually these organizations will be affected by the deployment of changes emanating from their headquarters-level organizations. These changes should support the ongoing efforts at improving quality organization-wide.

Current Status and Assessment of the DON Approach

Status of implementation. TQL began as a grass roots effort in the early . By 1988, it had become broadly embraced by the DON shore establishment primarily in the shipyards, aviation depots, and supply centers where the "customer" was quite clearly the sailors and marines in the operational Navy and Marine Corps. During this period the two-phase implementation approach was being researched and developed under the sponsorship of the Naval Aviation Systems Command. Early in 1989 the Undersecretary of the Navy assumed the leadership for TQL implementation. He formed the Executive Steering Group (ESG) and began an education process with those senior executives.

In June 1991, the Secretary of the Navy published a white paper on the subject of TQL implementation (l). Subsequently, the ESG developed and published strategic guidance related to the practice of quality (19). Neither of these publications have been published in the form of administrative policy nor implementation instructions.

Three organizations have been created to facilitate implementation of TQL. The Total Quality Leadership Office, staffed to the Undersecretary, was created to assist him and the ESG in all matters related to TQL implementation. The Director of that office is in the Senior Executive Service and is the personal advisor to the Undersecretary, as well as the Chief of *Naval* Operations. The CNO Fleet teams are two groups that were created for the purpose of assisting operational commands to develop process improvement efforts. Finally, TQL training has been established at the amphibious schools located at Little Creek (VA) and Coronado (CA). The staff of about 70 teach the six basic TQL courses and do some consulting with local commands.

Considerable progress has been made with regard to top-level support and involvement. However, the current level of involvement is considerably less since the change in administrations. The absence of a leader at the Secretary or Undersecretary level has served to put implementation in something of a limbo state. The monthly meetings of the ESG (now known as the DON Review Commission) have been discontinued.

The current situation has been exacerbated by the lack of policy guidance and implementing instructions. TQL is still generally regarded as something we "should" do, but Iine management has not been required to practice it. While it cannot be assumed that written guidance is sufficient, in the absence of visible leadership it may well be necessary.

Assessment of the DON approach. The real strengths of the DON approach are (a) adoption of the Deming/Shewhart quantitative approach and (b) delegation of authority to use this approach to the individual commands. A world-class training and training support program has been established to support these two features of TQL.

What is seriously absent from the DON approach is knowledge of, and commitment to, organizational transformation. As a result, numerous organizations have leaped headIong into strategic planning in the absence of an understanding of the organizational implications of TQL. Consequently, they develop strategic business plans (at best) believing that strategic planning, in and of itself, will lead to total quality. This mean-ends confusion (equating strategic planning with transformation to TQL) is similar to an earlier one that equated the use of statistics with process improvement.

The root of this problem is the failure to recognize TQL as a transformational change or a "paradigm shift," as it has become popularized. With the notable exception of those in the TQL Office, and a few students of organization development, there is little understanding that the word "total" implies much more than improvement in the quality of the products and services. Without a full appreciation of the need to change the culture and political structures--by those who can make these changes--it is quite likely that the phenomenal beginning of the quality revolution in government will suffer a "false start" *similar to* that of quality circles in the 1970s.

REFERENCES

1. Garrett, H. L. "Department of the Navy Executive Steering Group Guidance on Total Quality Leadership," 1991.

2. Walton, M. Deming management at work. New York: Putnam, 1990.

3. Deming, W. E. Out of the Crisis. Cambridge, MA: MIT/CAES, 1986

4. Moen, R. & Nolan, T. "Process Improvement". Quality Progress, September, 62-68,1987.

5. Tichy, N. M. Managing Strategic Change: Technical. political and cultural dvnamics. New York, Wiley & Sons, 1983.

6. Woolf, H. B. (Ed.) Webster's New Collegiate Dictionary. G. C. Merriam Company, Springfield, MA, 1975

7. Metz, E. "Managing change: Implementing productivity and quality improvements." National Productivity Review, 1984, 303-313

8. Kilmann, R. H. & Covin, T. J. Corporate Transformation. San Francisco: Jossey-Bass, 1988.

9. Mohrman, A. M., Mohrman, S. A., Ledford, G. W., Cummings, T. G., & Lawler, E. E. Large Scale organizational Change San Francisco: Jossey-Bass, 1989.

10. Huse, E. F. & Cummings, T. G. Organization Development and Change St. Paul MN: West Publishing Company, 1985.

11. Dockstader, S. L. What to do when there are more than five deadly diseases. Presentation to the MIT Conference on Quality and Productivity, San Diego, CA, 1985.

12. Dockstader, S., Doherty, L. & Shumate,E. Implementing the Deming approach to total quality management: A seminar. Navy Personnel Research and Development Center, San Diego, CA, 1988

13. Doherty, L., Dockstader, S., & Houston,A. Presentation to the Under Secretary of the Navy, San Diego, CA,

14. Dockstader, S. & Doherty, L. Resource requirements for TQL performance measurement and performance management systems. Presentation to the Under Secretary of the Navy, Pentagon, Washington DC, 1990.

15. Merton, R. K. Social theory and social Structure. rev. ed. G1encoe, IL: Free Press, 1957.

16. Ackoff, R. Creating the Corporate Future New York, Wiley, 1981.

17. Moss-Kanter, R. "Dilemmas of managing participation." Organization Dynamics, Summer, 1982.

18. White, M. & Konoske, P. "An evaluation of quality circles in the Department of Defense organizations." Navy Personnel Research and Development Center, (TR 89-9), April 1989.

19. Doherty, L., Howard, J. D. & Wells, D. "Strategic planning for organizational change." Presented at the annual conference of the Federal Quality Institute, 1993.

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Prediction of the Low Cycle Fatigue Life of HY-1OO Undermatched Welds in Marine Structures

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ABSTRACT

Finite element and analytical models are used in this study to predict the low cycle fatigue life of undermatched (lower yield strength) weldments of HY-100 steel. The objective was to determine the feasibility of replacing conventional overmatched welds in marine structures. Fatigue tests were performed on standard, smooth specimens, notched cylindrical specimens and a four point bend test on a full scale butt beam specimen. Numerical analyses were conducted using finite elements, with a two surface plasticity algorithm to simulate the cyclic behavior of the individual materials. The stress and strain concentrations at the notches were also evaluated using two analytical modelS: the Neuber and Glinka relations. The finite element predictions compared well with experimental data, and produced detailed predictions of the strain distributions, which were then used to assess the crack initiation life. Glinka's relation demonstrated superior predictive capabilities for local strains over Neuber's relation.

INTRODUCTION

In the past, overmatched weldments have been successfully used in the design of high strength steel naval structures. The high yield strength of the weld metal, in comparison to that of the base metal, ensures adequate strength and prevents the development of high strains in the weldment. Also, the performance of overmatched welds under low cycle fatigue loading conditions has proven to be adequate. However, for high strength steels, such as HY-1OO and above, the welding process envelope is severely restricted. For this reason, and for cost efficiency, undermatched welds have recently been considered in applications. Some of the major concerns that need to be addressed before actually using. the undermatched welds are their low cycle fatigue properties, their fracture resistance when subjected to both high static loads or dynamic loads, and the static strength of the weld during localized yielding.

For the past twenty years, numerous small scale and full scale overmatched weldments of HY series steels were tested, and the studies concluded that their fatigue crack initiation life generally fell into the same envelope. The scatter of the crack initiation of the weldments was usually more significant than that of the base metals (1,2). This is mainly because of imbedded defects, such as porosity, inclusion, and under-cut produced during welding. Local strains encountered in undermatched weldments could vary considerably from their overmatched counterparts. This is not only due to the difference in material properties, but also as a result of the different heat treatments applied during welding. In this study, the low cycle fatigue behavior of undermatched welds of HY-1OO steel has been invemigatcd.

Since low cycle fatigue is a local strain-dominated phenomena, the prediction of the local stress-strain response is crucial. Determining the notch root strain is usually difflcult, since the effect of the notch root constraint by the surrounding elastic material is quite significant. Several approaches were evaluated for their effectiveness in predicting the initiation of low cycle fatigue cracks at welded structural details. Analytical models such as Neuber's Rule (3) and Glinka's method (4), as well as computationally intensive two- and three-dimensional finite element models, were evaluated against experimental data. The analytical models are based on either plane stress or plane strain situations, so that when three-dimensional effects are present, the local strains predicted by these methods usually yield unsatisfactory results. Three-dimensional finite element models are more accurate in this respect.

Experiments consisted of fatigue tests on standard smooth cylindrical specimens, used to generate the baseline weld metal fatigue data. The specimens were oriented both along and transverse to the welding direction, so that the anisotropy of the weld could be investigated. Cylindrical notched specimens of weld metal, with different notch root radii to produce different notch root constraints, were also tested under cyclic loading conditions. Finally, a butt beam fatigue specimen, machined from a double-V joint welded plate, was subjected to a four point bend cyclic loading. This specimen consisted of base and weld metal, as well as the heat affected zone (HAZ), with a notch machined in the weld through the width of the plate.

The object of this study was to generate baseline low cycle fatigue data for weld metal to be used as the basic material property data for the numerical and analytical models. These models could then be utilized to predict notch root strains and cycles to crack initiation in structural components of various

geometries. Some **initial experimental and** modeling work for this study appears in (5,6).

TECHNICAL APPROACH

Low cycle fatigue crack initiation depends primarily on the strain range experienced at the crack initiation site. The accurate prediction of the local strain response is therefore most important. The basic concept of using the local approach for the crack initiation stage was outlined by Crews and Hardrath (7) in the "Companion Specimen Method - Equal Deformation Equal Life Concept." The main assumption in their method is that the notch root material and an unnotched specimen of the same material behave similarly, and show the same crack initiation life behavior. Therefore, the local stresses at the root of the notched specimen or component can be determined by first experimentally measuring the notch root strain and applying these local strains to the smooth' specimen. The resulting stress measured from the smooth specimen will then, according to this concept, correspond to the stress at the notch root. In other words, a smooth specimen can be used to simulate the material stress-strain response and damage accumulation at the notch root of a notched component.

The basic concept outlined above has been used in this study. Several smooth specimens of weld metal were cycled between various strain ranges, and the number of cycles to crack initiation was established for each strain range. Crack initiation was assumed to occur when a significant drop in material stiffness was observed. This set of experiments served to establish both the elastic-plastic material properties, and the low cycle fatigue properties of the weld metal. Similar experiments were also conducted on HY-1OO specimens, and testing is currently in progress on the HAZ.

Following these tests, the elastic-plastic material properties were fed into finite element models of notched cylindrical and notched beam specimens. Cyclic loading of a stabilized loading cycle was simulated on the models. The predicted strain range at the notch root of the models was then compared with the "strain range versus number of cycles to crack initiation" curve established from the experiments on smooth specimens. The number of cycles to crack initiation, as predicted by the numerical notched models was extrapolated from this curve. Similarly, notch root strains evaluated from Neuber's and Glinka's analytical models were compared with the experimental curves, and the number of cycles to damage initiation was extrapolated.

In order to validate the numerical and analytical models, experimental fatigue tests were conducted on notched specimens, and the measured values were compared with the model predictions.

EXPERIMENTAL PROGRAM

The experimental program was divided into two parts. The first involved obtaining the basic material property data, namely the cyclic stress-strain response and the baseline crack initiation data. The second set of experiments were fatigue tests performed on notched specimens. The data obtained from these tests was used to validate the accuracy of the numerical and analytical models. The specimens used to generate the cyclic stress-strain curves, baseline crack initiation data and failure life were similar to those stipulated by ASTM E606 (8).

Testing of Hourglass Specimens

Smooth hourglass shaped specimens were manufactured transverse to and along the welding direction for the weld metal, and transverse to and along the rolling direction for the HY-1OO steel base metal. The minimum gage section diameter of the specimens was 6.4 mm (0.25 in), each machined with a fine finished surface. Figure la depicts the typical geometry of these specimens. The purpose of these tests was to obtain the material cyclic stress strain response. The reason for using hourglass shaped specimens was to minimize to the possibility of buckling during compression. This type of specimen can generally reach higher strain ranges than the smooth straight specimen (Figure lb), before buckling.

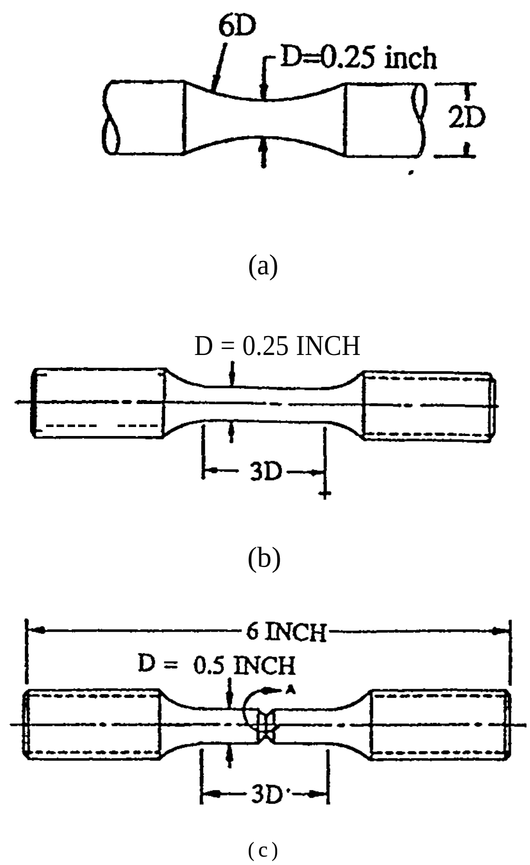

Figure 1. Schematic of (a) hourglass cyclic specimen, (b) cylindrical smooth fatigue specimen, (c) cylindrical notched fatigue specimen.

Incrementally increasing and decreasing strain controlled loading sequences were used, with the maximum strain reaching plus and minus 1.25 percent, A diametral displacement measurement gage was used to measure the deformations during cycling of the specimen. Poisson's ratio was measured as 0.295, and was used to calculate the axial cyclic stess-strain curve. A typical experimental loading curve for undermatched wd dl metal is shown in Figure 2. Comparisons were also made with HY-130, HY-80 and HY-NXI base metals. It was observed that the weld metal exhibited significant cyclic softening with a higher hardening exponent than its parent metal. There was little difference observed between the transverse or Iongitudinal cyclic stress-strain curves of either the base or the weld metal. The initial and stabilized cycles have been plotted in Figures 3 and 4 for the base and weld metal, respectively. Table I contains the average elastic modul measured from these tests.

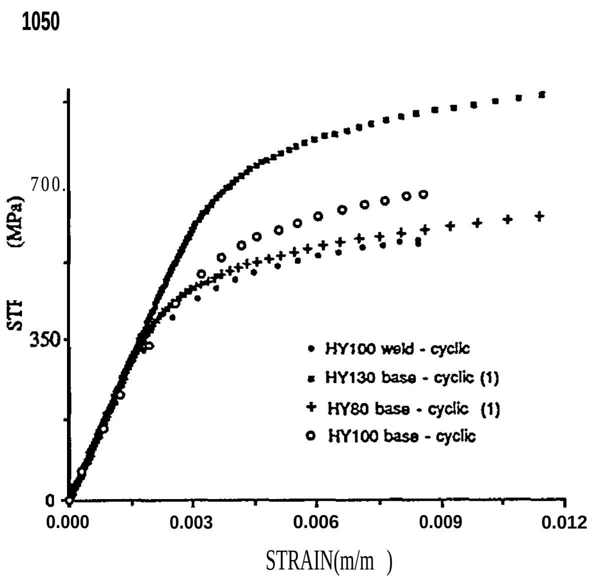

Figure 2. Stress-strain curves for weld metal, HY-1OO, HY-80 (1) and HY130 (1) Steel.

Material	First Cycle		Stabilized Cycle	
	Long. Mod. (GPa)	Trans. Mod. (GPa)	Long. Mod. (GPa)	Trans. Mod.
Base Metal	201.19	194.64	189.12	189.33
Weld Metal	203.81	206.98	188.43	205.81

Table I. Measured average values of elastic Young's modulus for HY-1OO base metal and weld metal.

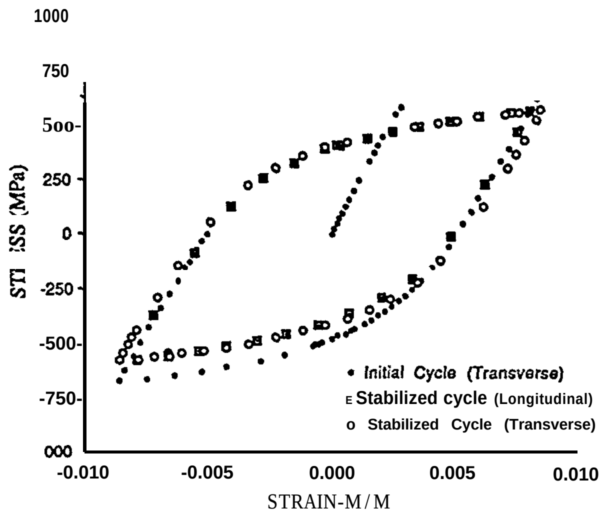

Figure 3. Initial and stabilized stress-strain hysteresis loops of the weld metal.

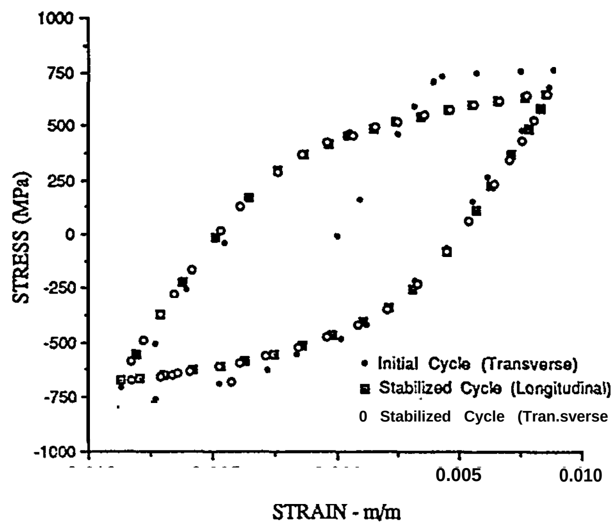

Figure 4. Initial and stabilized stress-strain hysteresis loops of HY-100 steel.

Testing of Smooth Fatigue Specimens

Smooth cylindrical tensile crack initiation fatigue specimens (Figure lb) with diameter 6.4 mm (0.25 in), were used to generate baseline weldment fatigue data. As before, specimens oriented transverse to and along the weld were considered to investigate the weldment anisotropy. Specimen surfaces were fine finished to avoid any artificial effect on their fatigue behavior. Strain control fully reversed loading ($R = \epsilon_{min}/\epsilon_{max} = -1$) was applied to all specimens. The load ranges were selected. from a nominal maximum

strain of 0.35 percent to 1.0 percent, such that the crack initiation or failure lives covered a range of approximately 1000 cycles to less than 50000 cycles. The cycle frequency used was 0.5 hertz. All tests were performed on computer-controlled servohydraulic tension-compression testing machines. The readings from the load cell and extensometer were recorded periodically. Crack initiation was defined to occur when the maximum load dropped significantly, indicating a drop in the stiffness of the specimen. Figure 5 shows a plot of the total strain range versus cycles to crack initiation for the weld metal. Also included are data for HY-80, HY-1OO, HY-130 base metal taken from reference (l).

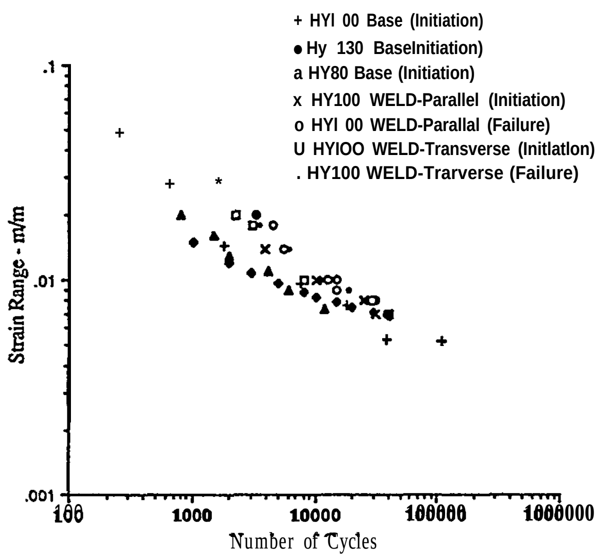

Figure 5. Total strain range vs. number of cycles to crack initiation or failure of HY-1OO welds. Data for HY-130 and HY-80 are from (l).

Testing of Notched Cylindrical Specimens

Testing of the notched specimens was performed using cylindrical specimens of weld metal with two different notch root radii, with the same notch depth. A schematic illustration of this type of specimen is shown in Figure lc. The specimen diameter is 12.7 mm (0.5 in) instead of 6.4 mm (0.25 in) so that the crack initiation and the failure could be defined more easily. For cylindrical notched specimens with 6.4 mm (0.25 in) diameter, crock initiation is usually difficult to detect before complete fracture occurs. The loading of the notched specimen was monitored using an extensometer, which was attached across the notch opening. The gage length of the extensometer was 25.4 mm (1.0 in) so that the recorded strains could be treated as remote strains. The notch root radii were 0.635 mm (0.025 in) for the type I notch, and 0.381 mm (0.015 in) for the type II notch. The notch depth was approximately 2.12 mm (0.0833 in), one-third of the radius. The notch root surfaces were also polished to have a fine finished surface. The loading was strain controlled, with R = -1.0 fully reversed load monitored by the extensometer, ranging from 0.15 to 0.35 percent strain amplitude. The crack initiation was assumed to occur when an abrupt drop was observed in the load sustained by the specimen.

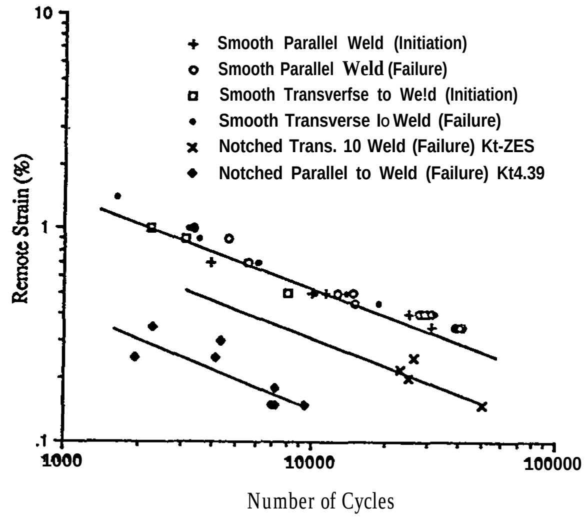

Figure 6. Comparison of the crack initiation life of smooth and notched specimens of HY-1OO weld metal.

As **with the smooth specimens, all tests were** performed on computer-controlled servohydraulic tension-compression testing machines. A comparison of the experimental crack initiation life between smooth and notched specimens appears in Figure 6.

Four Point Bend Test of a Full Scale WeIded Beam

In order to assess the fatigue crack initiation life for a full scale welded component of HY-1OO steel, a four point bend fatigue specimen was welded and machined, and loaded with a bending moment with loading ratio R = O (zero to tension loading). This specimen used a double-V joint weld plate with a welded inclusion angle of approximately 60 degrees. The dimensions of the four point bend specimen were 0.58 m (23.0 in) by 0.127 m (5.0 in) by 0.051 m (2.0 in) (length x height x thickness). A small through notch with notch root radius 0.4 mm (0.0158 in), and notch depth 2.41 mm (0.095 in), was machined near the HAZ to simulate the stress concentration of an under cut. The width of the heat affected zone was approximately 4.76 mm (3/16 in), located between weld and base plates. The specimen geometry is shown in Figure 7. A load of 320000 newtons (72000 lb) was applied at 0.089 m (3.5 in) on both sides of the center of the specimen to generate sufficient plastic strain at the notch root, while most of the specimen remained elastic. The strain was recorded periodically using Moire interferometry and a special high resolution grating technique; this was applied to the side surface near the notch root to obtain more accurate results. Strain fields were recorded periodically so that an entire strain vs. load history could be obtained and used later to compare with the finite element analysis. The

observation of crack initiation was performed on the notch root and side surface of the test specimen with the aid of a microscope and Moire interferometry. All testing mentioned above was conducted using a closed loop hydraulic tension-compression testing machine.

The yield strength of the HAZ was determined from micro hardness indentation tests. Due to the lack of uniformity of the material properties of the HAZ, the tests were conducted across its width. The average yield strength was found to be around 1241 MPa (180 Ksi).

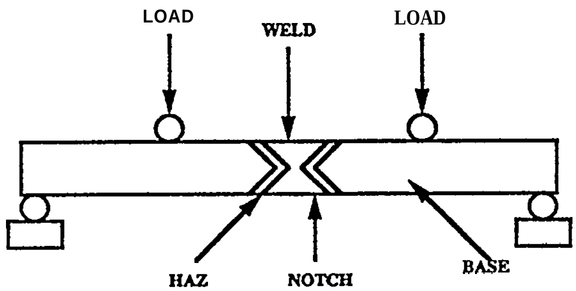

Figure 7. Schematic representation of the four point bend fatigue specimen. Dimensions are 0.58 m x 0.127 m x 0.051 m (23" x 5" x 2") (length x height x thickness).

NUMERICAL AND ANALYTICAL MODELING

It is usually quite difficult to accurately predict the notch root strain, as the effect of the surrounding elastic material on the notch root constraint is quite significant. In highly constrained sections the local root strains are difficult to predict. This constraint effect may affect fatigue crack initiation behavior (9). Current analytical notch root strain prediction models are either derived from plane stress, or plane strain situations. However, neglecting three-dimensional effects often yields unsatisfactory results. On the other hand, finite element techniques have the capability to model and analyze complex three-dimensional geometries without making unrealistic assumptions, which tend to oversimplify the actual loading conditions. It has keen demonstrated that, for fine-grained materials and moderately complex geometries, finite element predictions and experimental data show good agreement This is particularly true for the strain data along the loading direction (10). Two analytical models and the finite element method have been evaluated for their effectiveness in predicting the initiation of low cycle fatigue cracks at welded structural details in application.

Analytical Models

Two widely used analytical stress concentration strain prediction models widely used are the Neuber and Glinka relations. Their strain and stress relations are shown below:

$$K_\sigma \cdot K_\varepsilon = K_t^2 \qquad \text{Neuber (1)}$$

$$\frac{K_t^2 S^2}{2E} = \frac{\sigma^2}{2E} + \frac{\sigma}{n+1}\left(\frac{\sigma}{K}\right)^{1/n} \qquad \text{Glinka (2)}$$

where K_σ K_ε and K_t are stress, strain, and theoretical elastic stress concentration factors; S, σ, and n are the nominal stress, local stress, and Ramberg-Osgood hardening exponent respectively. Equation (2) is for plane strain situations.

Neuber's relation has proven to be very accurate in plane stress situations, such as the case of thin sheets with moderate strew concentrations. Glinka's model is an improved version based on the strain energy density for localized yielding. It has several modifications to handle plane stress and plane strain situations. Glinka's plane strain model has shown good agreement with experimental results for HY-80 steel in the past (10).

Numerical Models

Two- **and three-dimensional** finite element models were developed corresponding to the experimental notched specimens, so that the local stress-strain response could be computed and used to predict the crack initiation life. The solid models and finite element meshes were created using an interactive modeling software (11). A commercially available finite element code (12) was utilized for the computations. In order to accurately simulate the cyclic stress-strain response of the metallic materials, a two surface plasticity model was implemented in a user subroutine, and interfaced with the finite element program. This subroutine provided the code with the material behavior, returning to the main program the stress increment and instantaneous material stiffness for every strain increment supplied at each integration point in the model. The two surface theory is briefly described below with relevant references.

Two-Surface Incremental Plasticity Model

Plastic deformation occurs at material points where the stresses exceed the Mises yield condition. According to the flow theory of plasticity, the plastic strain rate, for an initially isotropic material, is given by Ziegler (13).

$$\dot{\varepsilon}^p_{ij} = (1 + H/3G)^{-1} n_{kl} \dot{\varepsilon}_{kl} n_{ij} \qquad (3)$$

where $\dot{\varepsilon}_{ij}$ is the total strain rate, n_{ij} is the direction of the outward normal to the yield surface at the current stress point, G is the elastic shear modulus of the material and His the instantaneous tangent modulus of

the stress-plastic strain curve. Plastic deformation causes the initial yield surface to translate and/or change size. In the analysis presented here, the center of the yield surface, α_{ij}, is assumed to translate kinematically according to Phillip's (14) hardening rule,

$$\dot{\alpha}_{ij} = \dot{\sigma}_{ij} \tag{4}$$

The size of the yield surface is assumed to remain fixed.

During cyclic loading, the plastic tangent modulus, H, varies nonlinearly with stress (or plastic strain). Here, His evaluated from the two-surface model proposed by Dafalias and Popov (15). This approach uses abounding surface which is an isotropic expansion of the yield surface. Initially the two surfaces are coaxial. During plastic straining the center of the bounding surface, β_{ij}, translates kinematically in the resultant direction of α_{ij} and μ_{ij}, (Figure 8). The unit vector μ_{ij} is along the line connecting the current stress point s and a corresponding point S on the bounding surface, both points having parallel outward normals. The rate of translation is given by

$$\dot{\beta}_{ij} = \dot{\alpha}_{ij} - \left(1 - \frac{H_0}{H}\right)\frac{\dot{\sigma}_{mn} n_{mn}}{\mu_{kl} n_{kl}} \mu_{ij} \tag{5}$$

where H_o is the asymptotic tangent modulus of the material's uniaxial response.

The instantaneous tangent modulus H is a function of the relative position of the two surfaces. It is computed from the formula

$$H = H_0 + h\frac{\delta}{(\delta_{in} - \delta)} \tag{6}$$

where δ is the distance between s and $\bar{s}$:

$$\delta = \sqrt{(\bar{\sigma}_{ij} - \sigma_{ij})(\bar{\sigma}_{ij} - \sigma_{ij})} \tag{7}$$

and n is a material property. The distance δ_{in} is the value of δ at the onset of yielding. Equation (6) indicates that when

$$\begin{aligned} \delta &= \delta_{in}, \qquad H = \infty \\ \delta &= 0, \qquad H = H_o \end{aligned} \tag{8}$$

For a uniaxial test the two-surface model leads to the scheme indicated in Figure 9. The parameters H_o, h, and the size of the bounding surface must be evaluated from the uniaxial experiments on the material of interest

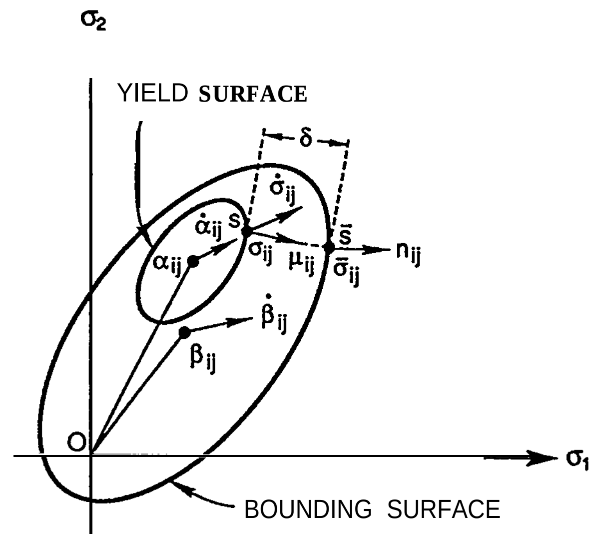

Figure 8. Schematic of the yield and bounding surfaces and their motion during plastic flow.

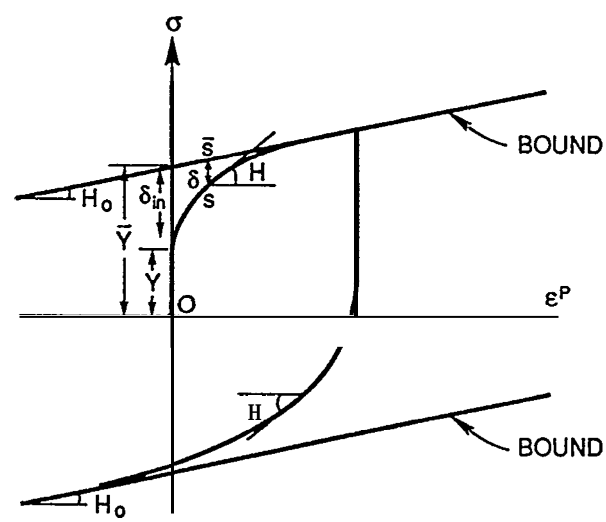

Figure 9. Evaluation of parameters from a uniaxial test for the finite element model.

Results

A three-dimensional finite element model of a 12.7 mm (0.5 in) thick double circular notched plate of HY-80 steel, with a notch root radius of 4.7 mm (0.185 in) and a width of 25.4 mm (1.0 in), was created. The purpose of this model was to evaluate the accuracy and validity of the two-surface plasticity theory in problems with high localized stress concentrations. Taking advantage of the symmetry conditions, only one eighth

of the actual specimen was modeled. Appropriate boundary conditions were applied to reflect the symmetry. The finite element mesh is shown in Figure 10. Three dimensional 20-node brick elements were used with reduced integration (8 integration points per element). The mesh comprises of a total of 721 elements, with the maximum number of elements near the notch root, where the steepest gradients exist. The material properties used for this simulation are given in TabIe II. The plasticity parameters correspond to the stabilized cycle of an experimental loading sequence on HY-80 Steel (10).

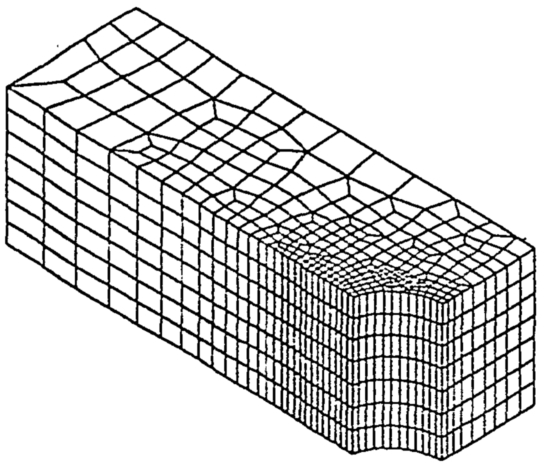

Figure 10. Three-dimensional finite element model of a 12.7 mm thick double circular notched plate (notch root radius 4.7 mm,width 25.4 mm).

The notch root strains along the loading direction from the finite element analysis have been plotted in Figure 11. They are compared with experimental data (10) obtained at the root of the notch using an interferometric strain/displacement gage (ISDG) (16) strain measurement system with a gage length of 100 micrometer Very good agreement is seen between the finite element analysis and experimental results, except at the end of the compression region, probably due to some sliding between the specimen ends and the grips, causing a slight rotation of the specimen. The interference pattern may lose its normality, which is required for an accurate measurement however, this discrepancy is minor, as can be seen in the figure. The satisfactory results obtained using the two-surface cyclic model provided confidence to conduct the finite element analysis for other notch geometries and material combinations. Reference (10) indicates that Glinka's plane strain model showed good agreement with experimental data, while Neuber's relation underestimated the strains due to its plane stress assumption.

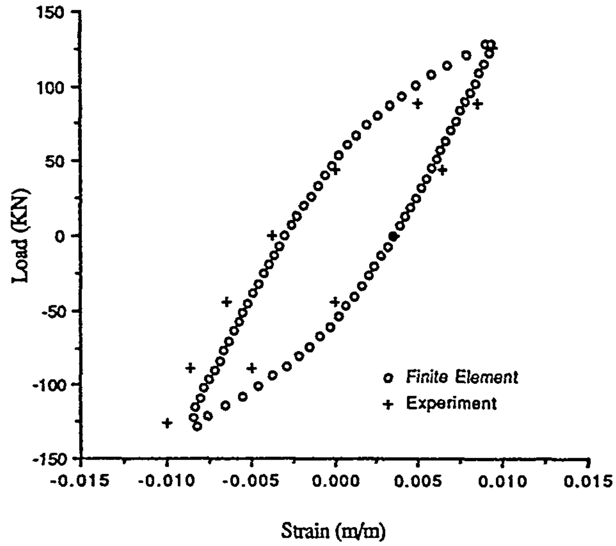

Figure 11. Finite element and experimental load vs. notch root strain curve from HY-80 double circular notched plate.

Cylindrical notched specimens were modeled with quadrilateral, axisymmetric, eight node elements. The dimensions of the models corresponded to those of the experimental specimens. Two notch root radii of 0.635 mm (0.025 in) and 0.381 mm (0.015 in) were used. Due to the symmetric nature of the specimen geomerry, only a quarter model was analyzed, with suitable boundary conditions. A typical finite element mesh is shown in Figure 12. Each mesh is comprised of 452 elements. Uniform surface pressure loads were applied on the unnotched end of the model. Materital properties for the

Material Property	HY-80 steel	HY-100 steel	HY-1OO Weld Metal	HAZ
Young's Modulus, E (GPa)	190.02	189.26	197.12	200.02
Poisson's Ratio, v	0.29	0.3	0.295	03
Yield Stress, Y (MPa)	299.92	330.95	159.96	1241.06
Tangent Modulus, (MPa)	7000.0	16750.0	9000.O	
Bound. Surf. radius (MPa)	510.0	600.0	490.0	
Hardening Param., h (GPa)	95.0	102.25	150.03	

Table II Material properties of HY-80 steel, HY-1OO steel, HY-100 weld metal and HAZ.

weld material were found from the uniaxial cyclic tests on the hourglass shaped specimens described earlier. The parameters used were for the stabilized cycle; they appear in Table II.

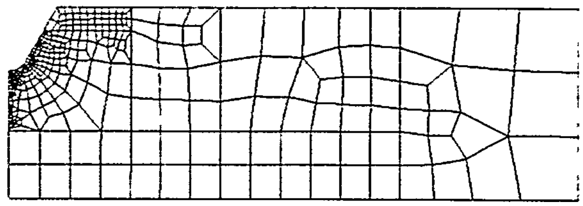

Figure 12. Finite element mesh of a notched cylindrical fatigue specimen.

The overall load versus notch root strain obtained from the finite element analysis has been plotted in Figure 13. The notch tip elastic stress concentration factors, K_t, were found to be 2.68 and 3.39 for radii 0.635 mm (0.025 in) and 0.381 mm (0.015 in) respectively. The finite element results were also compared with Glinka and Neuber strain prediction models, as shown in Figure 14. As can be seen here, the Glinka plane strain model, using the strain energy density concept, yielded excellent agreement with finite element analysis, while the Neuber relation loses its accuracy when higher plasticity and notch constraint are present. A comparison of the experimental and predicted fatigue lives is graphically represented in Figure 15.

Two- and three-dimensional finite element models of the four point bend fatigue specimen described earlier were also created. The model contains an HAZ thickness of 4.76 mm (3/16 in), between the weld metal and base metal, as shown in Figure 7. All other dimensions of the model correspond to those of the experimental specimen. Due to non-symmetry of the model, 760 8-node elements with 3003 nodes were needed for the two-dimensional model, and 154420-node elements with 6446 nodes for the three-dimensional model. The mesh used for either model is drawn in Figure 16. The loading applied was O to tension (R = 0) using nodal forces 0.089 m (3.5 in) from the center. Since the thickness of the four point bend specimen was 0.051 m (2.0 in), the notch produced near plane strain conditions so that the two-dimensional plane strain model yielded reasonable results. Material properties for HY-100 steel and the base metal are given in Table II. It was found that plastic deformation was localized at the notch tip and throughout the loading history; both the base metal and H&Z remained elastic.

Figure 17 shows experimental and numerical notch root strains plotted against load for the four point bend specimen. The experimental strains were recorded

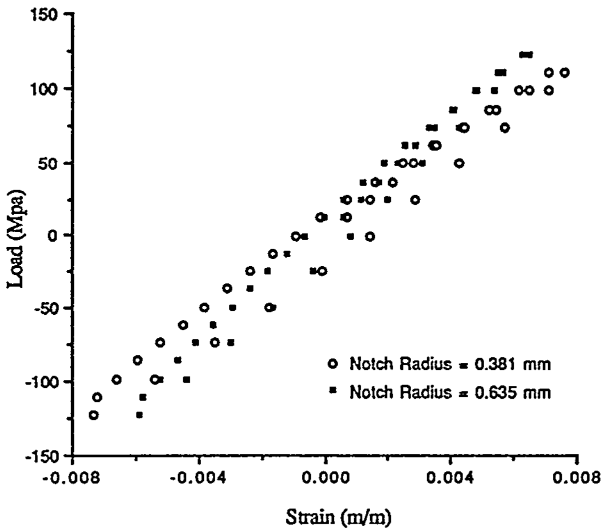

Figure 13. Overall load vs. notch root strain from finite element analysis of notched cylindrical fatigue specimens.

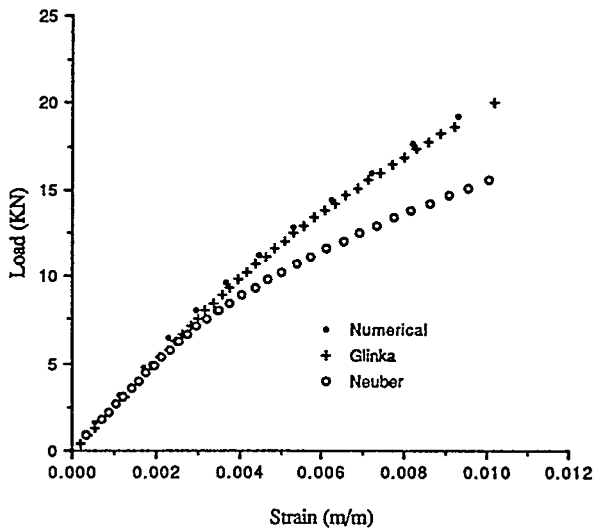

Figure 14. Notch root strain comparisons between finite element and analytical models for cylindrical notched specimens (notch root radius = 3.81 mm, notch depth =2.12 mm).

using Moire interferometry techniques. The agreement between the two is seen to be very good in the elastic range, however during plastic deformation the finite element predictions underestimate the actual strains. The numerical life prediction is compared with experimental results in Figure 15. The computed data points lie close to the 45 degree line, indicating fairly good accuracy of the numerical scheme.

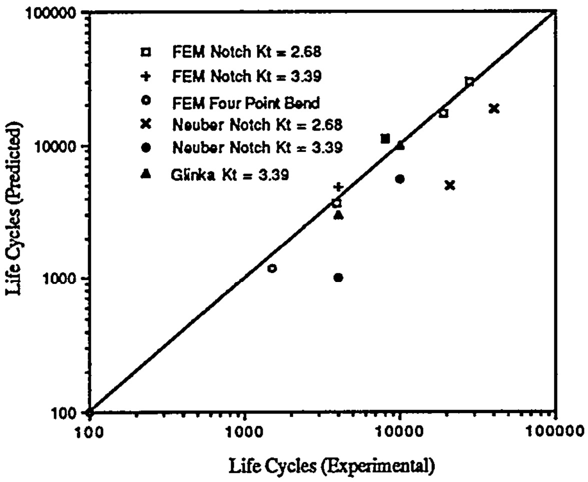

Figure 15. Comparison of experimental and predicted fatigue lives.

DISCUSSION AND CONCLUSIONS

The crack initiation life predicted by the finite element analyses and the Glinka and Neuber models were compared for their accuracy with experimental data as shown in Figure 15. The Glinka model captures the effect of constraint due to the presence of the sharp notch, while Neuber's relation is overly conservative in prediction of the crack initiation life of HY-100 under-matched welds, the finite element method, albeit the most expensive, provides the most reliable and accurate predictions of strain distribution to assess the crack initiation life. Glinka's prediction of the notch root strain works well for sharp notches and high stress concentrations, that is, when high constraints exist. The plastic zone surrounding the notch tip is relatively small. However, this is not true for Neuber's relation, which is based on the plane stress (less constraint) assumption. In general, Glinka's relations demonstrate better predictive capabilities for local strains than Neuber's relation, as is seen in Figure 14. The simplicity of calculating notch root strains with this method offers designers quick, inexpensive, and reasonably accurate results.

The baseline fatigue crack initiation and failure life obtained from smooth cylindrical specimens transverse to and along the weld are shown in Figure 5. Comparisons were also made between HY-130, HY-80 and HY-100 base metals. The differences between base and weld metal data are mom significant at higher loads. It is possible that due to the ductility of the weld, which has the lowest yield strength and a higher fracture toughness, the small fatigue crack propagation rate is lower than that of the base plate. At low load levels, fatigue controlled crack propagation resumed and the crack initiation behavior for the base metal and its weld became similar.

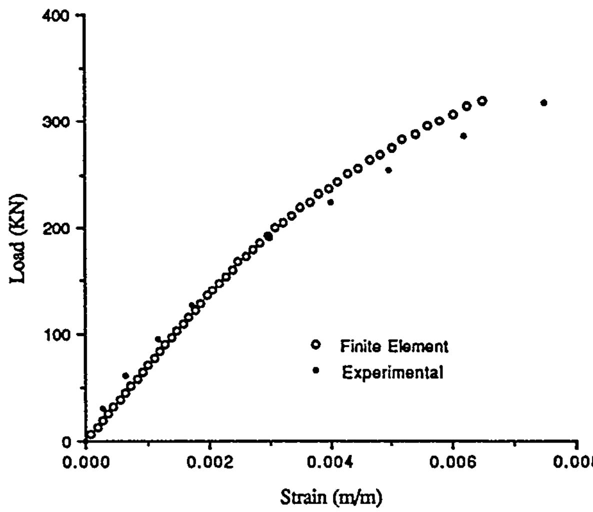

Figure 17. Experimental and finite element load vs. strain curve for a notched four point bend specimen near the notch tip.

The undermatched weldment of HY-100 steels shows similar baseline fatigue crack initiation life, although its yield strength is much lower than other HY series materials. More scatter was observed within the notched specimens than the smooth specimens. It must be noted that the grain size is quite large compared to the notch radius. The anisotropy at the notch root surface may be another contributor for the scatter of

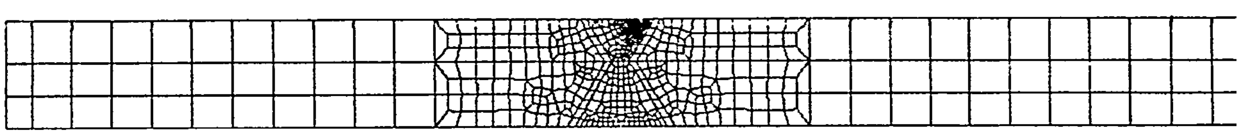

Figure 16. Finite element mesh of four-point bend fatigue specimen.

the tested results. Also, due to notch constraint effect, there is a build-up of multiaxial stress in the vicinity of the notch root. A best fit for the data set was found to obtain a single crack initiation or failure curve, which was then used in the finite element predictions. The finite element predicted crack initiation life of the four point bend fatigue specimen, using the stress-strain curves derived from hardness test, was reasonably close to the experimental results.

The results obtained from the modeling effort in this study demonstrated the effectiveness of the finite element method, and the two surface plasticity model, to predict the fatigue life of test specimens. The success of the analyses provides confidence to apply similar modeling techniques to structural components with more complex geometries. The experimental baseline fatigue crack initiation and failure life data can be used with the strain predictions from the numerical models to determine the life of the structural components.

ACKNOWLEDGEMENTS

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REFERENCES

1. Ellingwood, Bruce R. and Lomacky Oles, "Analytical Evaluation of Low-Cycle Fatigue Behavior of HY-130 Steel Baseplate and Welds: Naval Ship Research and Development Center, Report 4490,1974.

2. Czyryca, E. J. and Davis, D. A., "Low-Cycle Corrosion Fatigue Crack Initiation and Growth in HY-100 Steel Weldments," David W. Taylor Naval Ship Research and Development Center, DTNSRDC/SME83/64,

3. Neuber, H., "Theory of Stress Concentration for Shear-Strained Prismatical Bodies with Arbitrary Nonlinear Stress-Strain Law: Journal of Applied Mechanics, v. 28, pp. 544-550,1961.

4. Glinka, G., "Energy Density Approach to Calculation of Inelastic Strain-Stress Near Notches and Cracks: Engineering Fracture Mechanics, v. 22, pp. 485-508,1985.

5. Wang, K. C., Shah, R. S., Yuan, D., Kleinosky, M., J., "Low Cycle Fatigue Crack Initiation Life Assesment of HY-100 Undermatched Weld," 34th AIAA/A SME Structures. Structural Dynamics. and Materials Conference.AdalItive Structures Forum, Part 4, pp. 2371-2377, La Jolla, CA, April 19-22, 1993.

6, Wang, K C., Shah, R. S., Kleinosky, MJ., "Low Cycle Fatigue Crack Initiation Life Assessment of HY-100 Undermatched Weld and HAZ," 1993 SEM "50th Anniversary" Spring Congerence on Experimental Mechanic, Dearborn,MI (June7-9, 1993).

7. Crews, J. H. and Hardrath, H. F., "Companion Specimen Method," Experimental Mechanics, V. 23, pp. 313-320, 1966.

8. ASTM E606-80, "Standard Recommended Practice for Constant-Amplitute Low Cycle Fatigue Testing," Annual Book of ASTM Standards, Section 3, v. 3.01,1988.

9. Krempl, E., "The Influence of State of Stress on Low Cycle Fatigue of Structural Material -- A Literature Survey and Report" ASTM STP 770,1980.

10. Sharpe, W. N., Jr., Yang, C. G. and Tregoning, R. L., "An Evaluation of the Neuber and Glinka Relations for Monotonic Loading," Journal of Applied Mechanics, v. 59, pp. 560-566,1992.

11. I-DEAS User's Manual, Structural Dynamics Research Corporation, Milford, Ohio, 1990.

12. ABAQUS User's Manual, Hibbit, Karlsson and Sorensen Inc., Providence, Rhode Island, 1989

13. Ziegler, H., "A Modification: of Prager's Hardening Rule: Quarterly of Applied Mathematics, v. 17, pp. 55-65,1959.

14. Phillips, A., Liu, C. S. and Justusson, J. W., "An Experimental Investigation of Yield Surfaces at Elevated Temperatures," Mechanica v. 14, pp. 119-146,1972.

15. Dafalias, Y.F. and Popov, E.P., "Plastic Internal Variables Formalism of Cyclic Plasticity: ASME Journal of Applied Mechanics, v. 43, pp. 147-157,1976.

16. Sharpe, W. N., Jr. and Wang, K. C., "Evaluation of a Modified Neuber Relation," Journal of Engineerinz Materials and Technology, v. 113,1991.

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The Lay-Up and Reactivation of LNG Tankers: Lessons Learned

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The Liquid Natural Gas (LNG) Industry went from a projected boom in the 1970's to a contracted industry in the 1980's, when many ships were either permanently or temporarily laid up. In the 1990's, many laid up LNG carriers are being reactivated after as many as 12 years in lay-up. While the capital cost of an LNG carrier should dictate maximum preservation of the asset, the LNG industry is not immune to having to make hard economic decisions during slack times. In this paper, the authors present specific alternate lay-up procedures, together with the relative costs of these alternatives.

LNG carriers are steam vessels, as are many of the vessels in the Ready Reserve Fleet (RRF). However, many of the conclusions reached can also be applied to motor vessels, and as such could be of interest to operators and shipyards in all phases of the RRF program.

The subjects of dehumidification, inert gas plants, ballast tank coatings and drydocking, among others, will be discussed.

THE LAY-UP OF VESSELS - INTRODUCTION

Many students, who cannot bear to part with their restored auto when they go to college, but who also know it won't be able to travel that far, put the car up on blocks so that it may brought back to life again the following summer. As some may remember, the time required to restore the car to operation that following summer depended entirely on the care taken in laying up the car.

While no shipowner wants to think about lay-up, as it is not a particularly profitable mode of operation, the fact remains that for all trades and ship types, temporary, short term, or even long term lay-up is a possibility. As an example of ships that routinely lay up, the U.S. Great Lakes Fleet lays up each winter due to severe firming of lake water. The ships in this Fleet, however, are some of best maintained in the world, because this annual lay-up period is used to advantage. Because of the lay up procedures employed and the maintenance work carried out during the lay up period, these ships re-enter service in the spring with few problems.

Although lay-up means that there is no trade for a vessel and, therefore, revenue has stopped, there are maintenance areas where costs should not be cut, as asset depreciation will offset any potential, short term savings.

As an example of the merits of proper lay-up, the following account is relevant. A few years ago a container ship operator laid up two identical steam vessels. Identical De-Humidifying (D-H) equipment was installed on each vessel, and the same deactivation procedures were followed.

Ship A was laid up in Yokohama, Japan, and due to local law, the Master and Chief Engineer were kept onboard to tend the vessel. Ship B was laid up in Alameda, California, and, as a cost cutting measure no on-board personnel were retained. Instead, the vessel management staff and port engineering staff from the owner's California office visited the vessel on a regular basis, usually once per week.

Six months later both ships were reactivated. Ship A was reactivated on time and on budget, without any deactivation related equipment or motor loss.

Ship B, on the other hand, suffered damage to both main circulating pump motors, both main condensate pump motors, both forced draft fan motors, and both fuel oil service pump motors. As a result, the ship was delayed going into

service. The short term savings gained during the lay-up period of Ship B were eclipsed by the resulting increased reactivation costs and loss of revenue due to the delay in returning to service.

The U.S. Ready Reserve Fleet (RRF) ships are specifically intended, but not designed, to spend the majority of their time in a lay-up condition. The vessels are laid up in a manner intended to, hopefully, minimize reactivation costs and time. The reactivation of these ships has not, as demonstrated by the Desert Shield/Desert Storm mobilization, been as efficient and reliable as planned. One reason for higher than anticipated costs is the simultaneous reactivation of a large number of vessels into a diminishing number of shipyards available for ship repair and/or reactivation in the U.S. The limited amount of available reactivation shipyard resources produces a work overload, requiring significant overtime hours, and substantially increasing reactivation cost. The lay-up/reactivation program could be configured to even out the peaks and valleys and, thereby, balance lay-up and reactivation costs and improve ship availability. The purpose of this paper is to present ways in which to balance lay-up and reactivation costs.

In the Liquid Natural Gas (LNG) trade, the authors have gained considerable experience in laying up and breaking out steam powered LNG vessels. This experience has been gained over the last 20 years starting with the delivery, lay-up and breakout of the LNG carriers for the Algeria I LNG project in the early seventies. The Algeria I project was subsequently shut down and the tankers laid up in 1981. Finally, the restart of the Algeria to Cove Point, Maryland. LNG trade requires the reactivation of two of the ships laid up in 1981; this work is currently in progress. The experience gained, and the lessons learned, form the basis for this paper.

ATMOSPHERIC MAINTENANCE DURING LAY-UP

The desired end result of lay-up should be to hold the condition of steel, machinery and systems in a near-operating condition, and make allowances for environmental degradation. To carry out this aim, the principle method of preserving internal spaces is dehumidification.

Dehumidification Equipment.

Traditional Dehumidification Equipment (D-H) units remove moisture from the air by either heating the air and then moving it through desiccant towers, or by moving the air past refrigerant coils. The D-H units are temporary units which have to be mounted in either environmental structures or, if there is sufficient room, inside the house structure of the ship in order to provide protection from the elements. In marine, corrosive salt atmospheres, the life of desiccant type D-H units can be as short as one year, Similarly, non-marine refrigeration type D-H units are prone to corroding beyond repair in similar time periods.

Further, renting, moving and shipping D-H units for lay-up is expensive. For long term lay-up, D-H units run about $100 per day. For short term lay-up, $250 per day plus installation can be expected. Installation costs of either desiccant or refrigeration type D-H are similar, and are on the order of $10,000 to $30,000. The installation of temporary ducting, wiring, etc. increases the cost further. This ducting can also hamper repair work and general access to spaces. The cost of D-H equipment continues with the removal of this temporary equipment. Total temporary D-H costs, of either desiccant type or refrigerant type, are high enough to cause most owners to forego their use for a short term lay-up. However, short term lay-up often turns out to be longer than expected, and the ship suffers from lack of D-H during this period. The deteriorating effects of corrosion on the ship and equipment begin as soon as equipment is secured. Failure to dehumidify machinery spaces during even shott term lay-up can result in the need for expensive repairs at reactivation time.

In place of temporary D-H units, which must be installed whenever the ship is laid up and subsequently removed upon reactivation, refrigeration units intended for 40-foot containers can be permanently mounted in frames on the side of the engine room casing in a protected area. These units can be configured to run on electricity, diesel oil or Liquid Petroleum Gas (LPG), and can maintain D-H by means of refrigeration or heating. For short term lay-ups when the machinery plant is to be idled, the units need only to be activated. Machinery plant D-H is then immediately available, significantly improving the protection of the asset. The units cost approximately $11,000 each and can be installed by the crew. Shipyard installation adds an additional $10,000. Even without auxiliary ducting, the units will maintain an engine room at low humidity for short periods. However, for long lay-up

ate	T°F /H% Ambient	T°F /H% Lower Level	T°F /H% 54' Level	Comments
May '91	92°/78.8%	80°/ 54.4%	80°/44.5%	
July/August '91	85°/82%	86°/85%	88"/83%	1.
September '91	85°/75%	780/33.4	80°/32.7%	

TABLE I
Temperature & Humidity Readings with Traditional Desiccant Dehumidifiers

T = Temperature in degrees Fahrenheit
H = Relative Humidity in percent

1. The dehumidification equipment was secured during this period to allow for access to the engine room for maintenance, repair "and reactivation work.

Date	T °F / H% Ambient	T °F / H% Lower Level	T °F / H% 54' Level	Comments
March '92	53°/65%	56°/29.1%	58°/26.7%	
May '92	65°/100%	69°/52%	69°/50.8%	
July/August '92	90°/85%	78°/62%	80°/60%	outside doors open & unit running
September '92	75°/80%	65°/60.6%	68°/59.8%	outside vents open
January '93	42°/75%	54°/40.5%	56°/41.8%	vents closed & outside doors cracked

TABLE II
Temperature & Humidity Readings with Permanent Container Type Refrigerant Dehumidifier

periods, it is helpful to run light, flexible temporary ducting to the engine room supply blower(s) ducting, and thereby utilize the vessel's own ventilation system(s) to distribute the dry air. The addition of temporary ducting increases the cost of D-H. The amount of temporary ducting is significantly reduced over the use of totally temporary D-H systems, however.

Table I illustrates the maintenance of a dehumidified atmosphere with traditional D-H units. Table I can be compared to Table II which illustrates the maintenance of a dehumidified atmosphere with a permanently fitted container type refrigeration unit. In summer months, the permanent unit maintains the lower engine room at 12°F below ambient temperature during lay-up with considerable work taking place in the engine room. This data has been taken as a regular part of lay-up inspections aboard the LNG Carriers *ARZEW* and *SOUTHERN.*

Design Considerations of D-H Equipment.

D-H equipment is limited as to the volume

Features	Typical Temporary Desiccant Type Dehumidifiers	Typical Permanent Container Type Refrigeration Dehumidifier
Weatherproof	No	Yes
Heat & Cool	No	Yes
Maintenance Cost Ist Year	*$1,700.00*	*$0.00*
E.R. Access w/unit in place	No	Yes
Storage on Board	No	Yes
ABS & Lloyd's Compliant	No	Yes
Dimensions	9' x 4'-8" x 5'-8"	7'-4" X 6'-8" X 16"
Weight	2100 Ibs	1100 Ibs.
Price Less Installation	$15,130.00	$10,865.00

TABLE Ill
Comparison of Temporary D-H Units to
Permanent Container Refrigeration Units

of air that can be treated per unit time. Usually D-H systems are sized and designed to maintain a dry atmosphere once a space has been dehumidified, taking into account ambient air conditions and air infiltration. The time taken to reach acceptable D-H levels can be significant and is chiefly effected by the capacity of the D-H units, arrangement of ducting, and air infiltration. Consequently, dehumidified spaces must be sealed for best results, since frequent access to the space degrades the dehumidified condition of the atmosphere in the space. If a space must be frequently accessible, dehumidifying the adjacent passageway or providing an airlock (two separated doors) at the entry, may be required. As an example, the 600,000 cubic foot engine room of an LNG carrier using the permanent container refrigeration unit (with distributed ducting) at a rated air flow throughput capacity of 150 cubic feet per minute takes about one week to achieve satisfactory humidity levels throughout the engine room. With distributed ducting, therefore, approximately 2.5 engine room air changes are required to reach acceptable humidity levels.

By comparing Tables I and II it can be seen that the permanent D-H equipment installation was able to maintain comparable D-H levels to the temporary installation. Even during periods with high ambient humidity, July/August '92, and with the spaces open, the permanent D-H installation was able to hold the engine room humidity at an acceptable level. It was not possible to accomplish the same level of protection with the temporary installation. Table Ill compares features and particulars of typical temporary D-H units to a typical container refrigeration unit for use as a permanently installed engine room D-H unit.

Dehumidified air is the only method of atmospheric corrosion control acceptable for spaces accessible by humans. However, for spaces that are not accessible for personnel access, other alternatives exist. Specifically, corrosion can be controlled by reducing oxygen content in the atmosphere to the point that oxidation, or corrosion, is inhibited. There are two methods by which this may accomplished. The first is the reduction of the oxygen content by the combustion of hydrocarbon fuel in a stoichiometric combustion. These units are generally referred to as Inert Gas (1. G.) plants. The second method is by the use of industrial purity nitrogen. The method of oxygen control is by displacing the oxygen rich atmosphere with an oxygen depleted atmosphere.

Inert Gas Plants.

Tankers, LPG and LNG carriers are fitted with primary inert gas plants which put out a product gas principally composed of carbon dioxide and nitrogen; oxygen levels are less than 2% by volume. Cargo tanks which are piped to these systems can be inerted with this gas by displacing the atmosphere in the tanks with the oxygen depleted product gas, so that oxidation (corrosion) is halted through the lack of oxygen. When used in conventional tankers, however, this process does not guarantee that the cargo tank will be dry. Residual cargo or condensation can remain in the tank. This moisture can cause problems. For instance, conventional tankers generally use stack gas from the main engine as the feed gas to the I.G. plant, which cleans the gas by scrubbing before directing the gas to the cargo tanks. The gas produced in this manner may still contain sulfur and other stack by-products, that, when combined with moisture in the cargo tanks, will produce acids which can attack the tanks even though oxidation is reduced due to the lack of oxygen. The components of the product gas of any inert gas source must be verified, and the tanks thoroughly dried before laying up the tank in an inert atmosphere.

LPG and LNG carriers, on the other hand, are fitted with independently fired I.G. plants that use diesel oil as fuel and produce a much cleaner and dryer product gas: dew points are generally in the -60 degree F range. In as much as the cargo is very clean, with no residue left after discharge and warm-up, the use of the I.G. plant product gas for providing an inert, anti-corrosion atmosphere in the cargo tanks, is the standard method of preservation of the tanks.

While it may be tempting to inert ballast tanks or the ullage space over ballast water in ballast tanks, this should only be carried out under strict procedures where ballast tanks are sealed and proven tight, warning signs are placed on all access plates and surrounding enclosed areas are carefully monitored. Tank vents must be sealed to prevent routine breathing, but still provide over and under pressure protection. The composition of the product gas of the I.G. plant should be checked to ensure that acids will not be formed when in contact with the sea water and moisture in the ballast tanks.

It should be pointed out that both types of I,G. plants can produce dangerous levels of carbon monoxide. Priorto allowing manned entry into the space, the atmosphere should be checked not only for sufficient oxygen, but also for acceptable levels of carbon monoxide. Gas detection meters that read both oxygen and carbon monoxide concentrations must be utilized prior to allowing personnel to enter the space. In addition the personnel entering the space should carry the meters with them to continuously monitor the oxygen and carbon monoxide levels of the space.

Nitrogen.

As most LNG carriers use industrial grade nitrogen for inerting cargo tank barrier spaces, liquid nitrogen dewars and vaporization equipment are already in place. Dry nitrogen from the gas burning purge system can be circulated through boiler tubes, steam piping, turbines and gear cases. This will remove residual moisture from these systems, while providing an inert, dry, noncorrosive atmosphere for lay-up.

Using Liquid Nitrogen from the cargo system dewars during lay-up to dry out and/or maintain an inert atmosphere in the cargo tanks, piping, boilers, etc. is an excellent technique. There are drawbacks, however. While replenishment of liquid nitrogen at a lay-up pier is not a problem, replenishment at an anchorage would be very costly. In addition, liquid nitrogen at -320”F will crack service craft deck plates or ship steel if it is spilled in transit or during liquid transfer operations. Consequently, lay-up personnel must be trained in the safe handling of this cryogenic liquid. An alternative supply of industrial grade gaseous nitrogen has recently become economically available. Air separation plants provide ambient temperature nitrogen by membrane separation of air or by pressure swing absorption techniques.

Air separation plants not only eliminate recurring liquid nitrogen purchase costs, but also provide an unlimited nitrogen supply regardless of ship location in lay-up, as they require only electric power to operate. This same unlimited supply of nitrogen also permits control air systems, etc. to be purged with nitrogen, thereby improving system longevity. Power consumption is comparable to that required for an air compressor to supply the desired delivery pressure and flow rate. The plants generally pay for themselves in less than a year depending upon total nitrogen consumption.

Remotely Located Spaces.

It is difficult and probably not cost-effective to totally dehumidify spaces such as the bow thruster rooms and steering gear rooms using the previously described methods. In these remote spaces, heating strips, small portable desiccant type D-H units and, sometimes, refrigerant type D-H units can be employed, either by themselves or in combination in a localized fashion to protect specific equipment. Preservative coatings can also be applied to further inhibit corrosion. Care must be taken to use a coating that is easy to remove or does not require removal prior to reactivating the equipment.

ALTERNATIVE PRESERVATION TECHNIQUES

While atmospheric control by dehumidification is the generally preferred method of preserving equipment during lay-up, rotating and operating equipment and other preventive maintenance techniques will also provide good results. The principle draw back to employing this technique is that it requires a larger, permanent, skilled staff to perform the extensive maintenance routines required.

This technique was employed on the LNGC *HOWARD BOYD* in March of 1980. The ship delivered a cargo to Cove Point, Maryland and was taken out of service for what was expected to be a short term lay-up, approximately 30 to 60 days. The ship was sent to sea to gas free and inert its tanks. Upon gas freeing, the vessel was laid up at Norshipco, and then, subsequently, transferred to the coal terminal in lower Newport News, Virginia after the short term lay up developed into long term. The top five officers were retained on board the vessel. All other officers and unlicensed crew were discharged. The officers retained on board undertook an extensive lay-up routine and comprehensive preventive maintenance program on the vessel.

All systems were blown down first with air and then with dry nitrogen from the ship's liquid nitrogen dewars. In lieu of dehumidifying machinery spaces, etc., equipment was rotated and operated on a regular basis, and the required preventive maintenance was undertaken. Due to these efforts, in August of that year, the vessel was reactivated in less than forty (40) hours with no failures, and subsequently sailed to the Mediterranean.

Had the lay-up been extended much longer, however, the cost of maintaining the ship in this fashion would have escalated to the point that long term lay-up techniques would have had to have been initiated. It is difficult to predict precisely how long a ship may be required to remain in lay-up. It is, therefore, equally difficult to make economic assessments of the most cost effective lay-up techniques. Had the LNGC *HOWARD BOYD* been fitted with a permanent D-H system, long term techniques could have been initiated immediately, which would have ultimately reduced the lay-up costs.

CONSTRUCTION DETAILS THAT IMPROVE LAY-UP

There are a variety of details and equipment that can be added during construction that will reduce cost the of lay up. Many of these details will also reduce ship maintenance costs.

Towing Fittings.

Towing fittings consisting of deck-mounted towing pads and specially radiused chocks will soon be required to be fitted to tankers as a salvage feature. For any ship in lay-up, towing fittings with pendants to the water give an added measure of safety should the ship be blown off a dock, or somehow lose its anchor gear while at anchor. Towing fittings also allow the ship to be readily and easily towed from lay-up as an alternative to crewing the ship and transiting under its own power. It is often necessary to change lay-up berths. Towing the ship eliminates the expense of reactivating the machinery plant and subsequently reinstating the lay up.

The authors recommend installing these fittings at each end of the ship. The construction and mounting of these fittings as a refit on the bow only, with the ship alongside a pier with crane service available, will cost about $20,000. If the towing fitting is installed while at an anchorage, the cost can be expected to be in excess of $50,000. The cost of installing towing fittings during construction should be significantly less than the retrofit cost.

Stainless Steel Kickpipes.

In 10 years of lay-up, the subject LNG Carriers, which have flat decks, pocketed rain water even though they had stern trim. Deposited salts from

operation, together with this wet condition, corroded approximately 60 kickpipes per ship. Even kickpipes that appeared to be sound were found to have pin holes when the decks were recently sandblasted. Water seeped into voids, cofferdams and other spaces though these kickpipes, causing undetected corrosion and coating breakdown. Although the extent of interior corrosion does not, at this time, warrant plate renewal, it is still necessary to remove the corrosion and repair the coating(s); this will be more expensive than it would have been to install stainless steel kickpipes in the first place. Additionally, the cost of renewal of the deteriorated kickpipes will be quite expensive, in excess of $50,000 per ship. The high cost of renewal is due to the necessity of disconnecting the electrical connections, removing the cables from the kickpipes and then reinstalling and reconnecting the cable after the kickpipe has been renewed. As a further complication and expense, many of the cables terminate at explosion proof hardware which has to be destroyed in order to remove the cable. A significant maintenance problem could have been avoided for a very modest cost during the construction of the ships.

Inset Side Mooring Fittings.

The height of LNG carriers makes them unsuitable for most lay-up piers with respect to the lead of mooring lines. A similar problem exists with car carriers, some Roll-On/Roll-Off Ships (RO/RO) and container ships. For breast lines, in particular, unless there is sufficient land between the ship and the shore, bollard leads will be nearly vertical. In extreme conditions, LNG carriers have pulled shore fittings out of the ground. The release of just one shore fitting, combined with the huge sail area of an LNG carrier, has been sufficient to cause the parting of remaining mooring lines and the unscheduled departure of an LNG Carrier in lay-up.

inset chocks should have a horizontal pull capacity of at least 100 tons and should be mounted about two to three meters above the deep load line. The bar-type fitting allows multiple cable passes for lay-up, while the horn type may be easier to use for tug assistance, when docking.

Stern Anchor.

Fitting a single wildcat, aft windlass and centerline hawsepipe with chain and anchor provides greater flexibility with regard to lay-up berthing arrangements. For fiord type lay-ups where the stern can be brought close to shore, the stern anchor can be slipped and the stern chain taken ashore. The stern chain can be tensioned at any time allowing adjustment to shore power lines and piping/hose runs. Temporary anchorages for lay-up are also possible in restricted waterways by utilizing the stern anchor to reduce ship swinging and surging. Even at pier side lay-up berths the stern anchor provides added security to the ship's mooring arrangement when severe weather conditions exist.

The installation of a stern anchoring system is an expensive new construction option. Costs can be expected to be approximately $750,000.

House Deck Drains.

The house deck drains on the subject LNG Carriers are typically 38mm to 75mm in diameter, and are continually being plugged by falling paint, debris or dirt. The effort to clear the drain strainers and the pipes themselves takes up a considerable amount of a lay-up crew's time (approximately 640 manhours per year) and, presumably, operating crew time when the ships are in service. Larger drains with easily removable inlet screens and without horizontal runs, including sloped horizontal runs, would minimize the problem. Many of these drains run internally to the house, which further complicates maintenance and ultimate replacement. Although internal drains may look nice, they are usually more expensive to install during construction, in addition to being more expensive to maintain. External drains of Glass Reinforced Plastic (GRP) or similar non-corrosive material, where practicable, with a sufficient number of cleanouts to allow direct access to all straight piping runs, would be beneficial to long-term maintenance both in service and in lay-up.

Stack Cover and Access to the top of the Stack.

As all current LNG carriers are steamships, they have boilers which, in lay-up, may or may not be cleaned depending upon time in service since last cleaning, and expected length of lay-up. Regardless of the degree of cleaning, rain water entering the boilers through the stack can soak the floor as well as mix with the residues from burning residual fuel oil, causing corrosion

and totally destroying floor tubes in a short period of time. Tarpaulins over the stack frequently fail in rainstorms, thus a more permanent stack cover is recommended. Access to the top of the stack for installing such a permanent cover without the use of crane or other shoreside services is also recommended.

BALLAST TANK COATINGS

The ballast tanks on the LNGC'S *ARZEW* and *SOUTHERN* were coated with an epoxy based coating system, which has held up extremely well in both dry and wet tanks. Some of the ballast tanks have been filled for over 10 years with no breakdown or blistering of the coating. Humidity control during coating and quality control of the original coating application are credited as the main reason for this outstanding performance. The coating itself has low water permeability, and was applied in excess of 8 roils (D17), Careful attention to the surface preparation and coating of flanges, relief holes and brackets is also evident. The small areas of coating breakdown that have been found will be fitted with anodes during reactivation; no recoating, therefore, is planned. Ballast tank coating is the single most important factor to double hull LNG tanker longevity. Saving construction costs in this area is false economy.

PRE-REACTIVATION WORK

The subject group of LNG carriers were laid up in 1981 and stayed in continuous lay-up until their purchase in late 1990. Upon transferring title to the ships, they were moved, by towing, to a new lay-up berth. Once lay-up procedures were reinstated after the tow, critical sections of the ships and equipment were opened up for inspection in preparation to preparing a reactivation work specification. The water side of the boilers, the cargo and ballast tanks and the internal spaces of the ships were all found to be in excellent condition. In addition to the lay-up procedures previously discussed, the vessels were, and continue to be, manned continuously during the lay-up periods. A lay-up routine consisting of rotating machinery, preventive maintenance, and checking electrical equipment was, and continues to be, followed. Since bringing the ships out of deep lay-up and beginning the reactivation process, all electric motors, switchboards, control consoles and electronic systems have been powered up with little deterioration noted. The decisions to replace and/or upgrade equipment will, therefore, be based on current and future supportability rather than on equipment deterioration.

The charterer of the ships desires a relatively quick (90-day) reactivation period. In preparing and planning for reactivation, personal computer based project planning and management software was utilized to develop an overall Program Evaluation Review Technique (PERT) chart for pre-reactivation work, long lead equipment ordering requirements, yard reactivation, gas and sea trials, positioning voyages, etc. A portion of this chart is shown in Figure 1. This section shows the detail of planning for long lead equipment purchases. The first charts produced were astounding, indicating that years would be involved in the reactivation process, far from the ninety days desired by the charterer. Estimates were refined and reactivation specifications were prepared which were bid to a number of U.S. shipyards. In submitting their bids, the shipyards estimated the reactivation shipyard period to be between 8-1 /2 and 9 months. Subsequent meetings with the shipyards and review of scheduling revealed that out of over 400 reactivation tasks, approximately 14 tasks took the reactivation period beyond 4 months time. Those 14 tasks have been the subject of close examination, in order to bring the reactivation period closer to the ninety days desired by the charterer. The following work was undertaken as a result of reactivation PERT chart evaluation.

Turbines.

Lead times for replacement parts for the main and generator turbines were found to be up to one year. Consequently the turbines were opened up for inspection so that any parts that may have been required could be ordered in sufficient time. Upon inspection some very long lead parts were found necessary. The turbines were left opened up and D-H reinstated by installing temporary plastic enclosures over the casings. The parts were ordered and when received, many months later, the turbines were reassembled. This removed a long lead item from the original schedule that in fact had not had sufficient time scheduled in the reactivation plan due to the unknown need for long lead replacement parts. Since the work is now completed, it has been deleted from the

Typical PERT Chart Detail

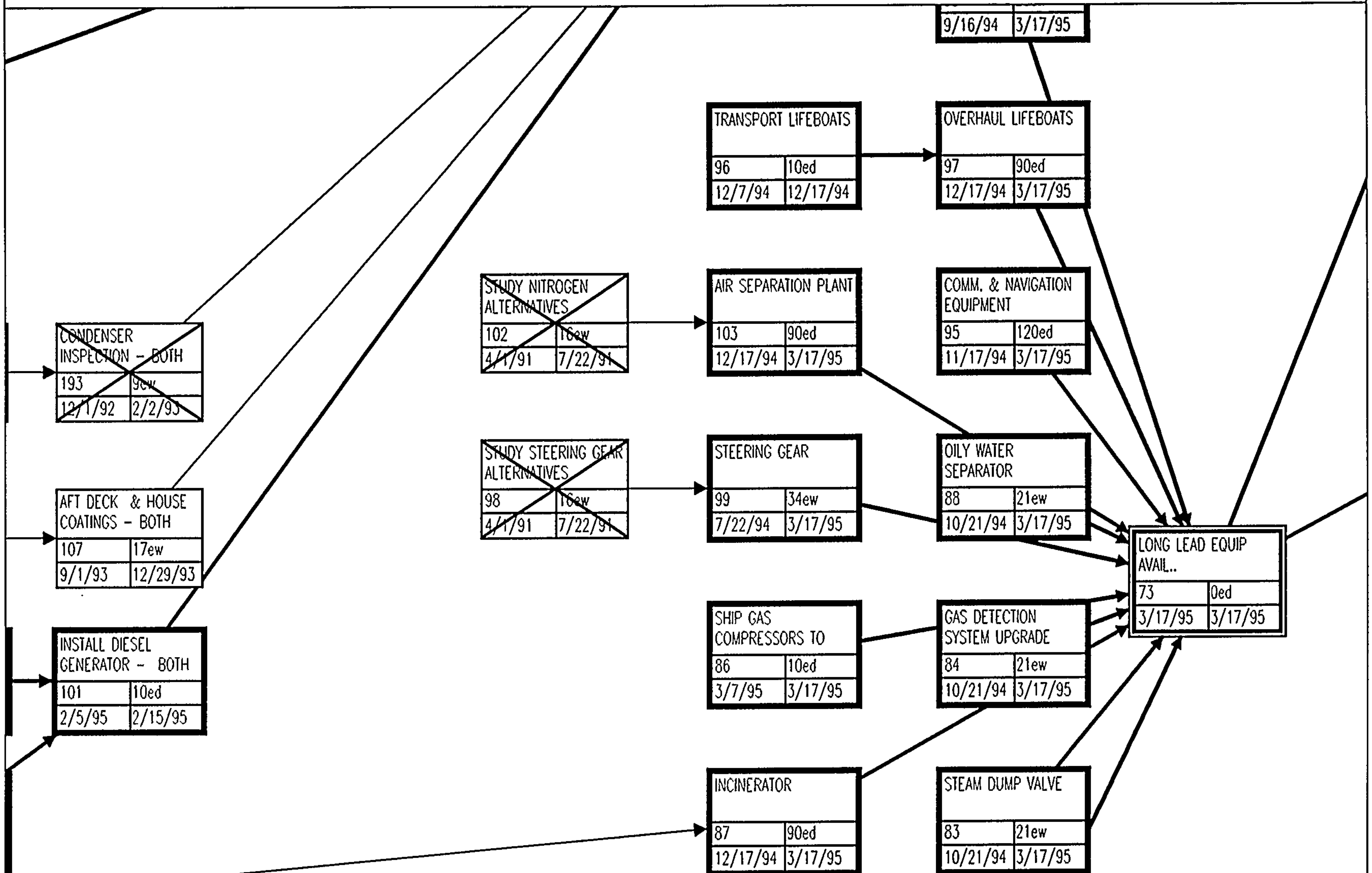

Figure 1

reactivation work plan and schedule.

Boilers and Condensers.

Boilers and condensers were also of unknown condition and, therefore, subjected to long schedule times to plan for the worst case. The boiler refractory was removed and the tubes were cleaned. This allowed detailed examination of the condition of the boiler and permitted shorter schedule times to be used with greater confidence. Similar actions were taken with the main and auxiliary condensers.

Pumps.

Large pumps in the engine room, such as the main circulators, etc. were also subjected to long schedule times due to unknown condition. In particular, the condition of pumps used to ballast/deballast the ship in lay-up were suspect due to long periods in the corrosive seawater atmosphere; this is because the pumps had to remain in service and could not be put under a lay-up condition. Like the turbines, the engine room pumps have all been overhauled prior to full reactivation and the work removed from the reactivation, work plan and schedule.

Cargo Pumps & MI Cables.

Electrical problems with other, similar pumps/and Mineral Insulated (MI) cables on other vessels dictated an assessment of the cargo pumps. Like the turbines, if parts were found to be necessary during reactivation, lead times could be as high as one year. As a result, all of the cargo pumps were removed and rebuilt using new bearings; the submerged electrical ends were thoroughly tested and then reinsulated using the vacuum impregnation process with an epoxy insulation for the field winding(s) which is suitable for cryogenic temperatures.

Deck Electrical Junction Box and Cargo instrumentation.

Similar lead time problems were also found with regards to instrumentation systems in the cargo system, Overhaul of this ‘equipment is currently being carried out prior to shipyard reactivation.

Cargo (Cryogenic) Valves and Valve Actuators.

Several valves were opened up for inspection. Approximately 90% of the valves inspected had damaged soft seats and seals. Lead time on replacement parts was approximately 10 months. Due to the critical nature of this equipment, the decision was made to replace all soft components in all of the valves and perform the overhauls prior to shipyard reactivation. As the valves are being overhauled, further component replacements have been found with similar lead times.

Gas Compressors.

The original equipment manufacturer was no longer in business. A qualified service representative had to be located. Any parts needed had to be fabricated on a custom or “one-off” basis. As with items already discussed, the potential for massive schedule delays was very high due to long lead times on parts. The compressors were removed and shipped to the service company. They have been overhauled and are in storage under the care of the service company until needed during shipyard reactivation.

The following reactivation work items were identified as having significant schedule impacts after reviewing the shipyard prepared schedule and planning documents, with the bidding shipyards. Although these items do not have unknown long lead part requirements, they do impact the overall schedule due to conflicts with other reactivation work.

Blasting and Coating of the Trunk and Main Decks.

The blasting and coating of the trunk deck was an intricate job due to the large amount of deck equipment, piping and related outfit. In addition, the deck was showing severe corrosion in many areas due to standing water during the ten years of lay-up. For these reasons the trunk and main decks forward of the accommodation house were blasted and coated during the summer of 1992. The job turned out to be significantly more time consuming than expected, and would have caused massive schedule delays had it been performed during the shipyard reactivation period. The masking job alone ended up taking two weeks, far in excess of the time scheduled. Due to environmental considerations, clean-up involved tremendous vacuums and hoppers that had to be loaded/unloaded at least daily and repositioned more than once each day. The entire

job, per ship, was estimated at 90-120 days in good weather, and ended up exceeding this time by a considerable amount. This posed a scheduling problem, increasing total reactivation time, since nothing else could be done on deck or in the cargo tanks during the entire blast/coat job. By performing this work prior to the shipyard reactivation period, the planned reactivation time was reduced and the further deterioration of the deck was averted.

Blasting and Coating the Aft House.

While the blasting and coating of the aft house will be a less intricate job than the trunk deck work, it still requires significant masking and covering of the front of the house to limit grit blast damage and clean-up to just around the house area. During the 90-day period in which the blasting and coating work is to take place, each yard assumed little or no engine room work will be carried out as most all access to the house and casing will be sealed. If these seals are violated, then engine room machinery work could become contaminated. Consequently, the blasting and coating of the aft house has been designated as a pre-reactivation project and is currently scheduled for the fall of 1993.

Most yards agreed that if the trunk deck and aft house blasting and coating tasks were carried out before entering the reactivation yard, that topside and bottom painting could take place in drydock with interdiction barriers placed between the sheerstrake and drydock wingwall. In this way, work above the sheer strake could continue while the ship is in drydock.

Auxiliary Diesel Generator Room.

The ships are to be retrofitted with a standby Diesel Generator (D-G). A new room is to be fitted below the main deck in an existing stability tank. The stability tank was not used in service and is in a convenient location. The work involves slotting the deck to rig plate through for steel fabrication, mounting a large diesel generator and switchboard, and then running electrical and ventilation services in the new room and to the Engine Room. Carried out in conjunction with other work in a short term reactivation, this installation blocked the major casing access to the Engine Room and blocked major pathways across the ship for handling materials for other tasks.

Opening up the deck slot, dumping the prefabricated steel below deck and quickly closing the slot would solve most of the deck interference problem. However, this approach would create a bigger problem below deck in attempting to sort and move prefabricated structure in a confined space. If this steel work were to be completed and the D-G set and switchboard installed, all the shipyards agreed that the remaining electrical, ventilation, testing and other work could be carried out in a 4-month reactivation period. As with the aft house blasting and painting, this work has been designated as pre-reactivation and is scheduled for early 1994.

Cryogenic Work.

Cryogenic work covers many cargo related items on deck and in the cargo tanks, where a clean, undisturbed workplace is necessary. Lifts must be carefully made under controlled conditions as any resulting damage could be extremely expensive and could delay schedules significantly. Again, in discussing schedules with the bidding shipyards, it was clear that some shipyards had stopped all other work in the vicinity whenever cryogenic equipment work was undertaken. It also became clear, upon reviewing shipyard bids, that technical expertise with regards to cryogenic equipment varied widely between the bidding shipyards. Cryogenic repair work, such as cargo pump overhauls, etc. was, therefore, designated as pre-reactivation work. The cargo pumps were removed, overhauled and reinstalled in 1991 & 1992. Other cryogenic work continues in accordance with the pre-reactivation work plan.

PRE-REACTIVATION PLAN

Working with the shipyard in which the LNG carriers are laid up (that shipyard is also bidding on the reactivation work), quotes were solicited for doing the above tasks prior to reactivation as separate pre-reactivation work items. As noted, competing shipyard bidders agreed to the items that should be carried out. The order or priority under which pre-reactivation tasks were/are carried out is based upon: preservation of the ships and the capital asset that they represent, budgets and, lastly, a logical sequence of work from a technical viewpoint. Preservation of the ship is based upon preventing further degradation of the ship and equipment. It was for this reason

that the trunk deck blasting and coating was one of the first tasks to be performed. As with all projects, there are also budgetary considerations. The principle budgetary constraint is to delay all outlays as late as possible consistent with preserving the ship and reducing the reactivation period. A logical work sequence is important, but has been overridden in several instances by the need to preserve the ship and delay cash expenditures, For instance, logically it would be preferable to do the steel work for the diesel generator room prior to blasting and coating the main deck in this area. Unfortunately, budget constraints and the need to prevent further degradation of the main deck override logical work sequence, therefore the blasting and coating will be performed prior to the diesel generator room steel work. This means that repair of the coating on the main deck, therefore, will be required, increasing overall cost slightly.

The cost for carrying out these tasks at subcontractor's (and shipyard's) convenience, without the intefierence of other work was 15 Yo to 30% less than the bid figures for the same task in reactivation. All reactivation tasks were bid by the bidding shipyards as stand alone tasks, where overhead and other costs were included in the items. Therefore, direct comparisons between doing a task during the reactivation period and doing the task as pre-reactivation work could be made.

By carrying out one to three major tasks simultaneously as pre-reactivation work, they can be supervised and inspected unencumbered by the press of a reactivation schedule deadline. Although accomplishing work within the planned schedule is still important, the schedule can, nonetheless, be adjusted when needed with greater flexibility without the press of an in-service date for the ship. Costs can also be readily controlled to the satisfaction of owner and contractor.

The trunk deck coating job is an example of the quality that can be achieved when the schedule allows flexibility. This work was accomplished in the spring and summer of 1992, and ended up being performed during an extremely rainy, wet spring. Consequently it took almost twice as long to complete as predicted. The blasting work and subsequent painting with a inorganic zinc/surface tolerant epoxy coating system cost nearly three-quarters of a million dollars per ship. Properly done, the system should last at least 10 years with reasonable maintenance. If this work had been accomplished during the reactivation period, the press of an in-service deadline would have required that less than optimum conditions for applying the coating system be accepted in order to meet the schedule. The final job would have been inferior to the job carried out in pre-reactivation. if the work had been accomplished under these conditions, and coating breakdown occurred in two years, the cost to carry out a coating job at sea or to remove the ship from service would be much higher than the cost of the original work. Doing such work at sea with entrained salts and a damp atmosphere would also give limited service life to the coatings.

LAY-UP MANAGEMENT

While Figure 1 shows a portion of the Macro Reactivation Plan, consideration also had to be given to the management of the continued lay-up of the ships. The minimum manning in lay-up (with no lay-up maintenance routine) consists of three watchmen on a 24-hour rotation. The annual cost of labor under such an arrangement is estimated at $91,250. Unsecured lay-up berths on the East Coast, where guard service would be required, ranged between $500 and $2,500 per day depending on the length of lease and available shore services. Full utilities (power, water, steam and sewage) ranged between $250 and $350 per day. Assuming a lower median cost of $1,000 per day for berth and services, the total estimated cost for guards and a berth is $456,250 per year, without performing any maintenance or preservation work.

When reviewing the critical work items discussed previously, it was clear that a shore crane would be helpful in carrying out these tasks. Man-handling equipment over pipelines and down deck slopes was thought to be inefficient and dangerous. A lay-up berth with a higher level of services, therefore, was sought.

A lay-up berth was located in a secure shipyard where the increased berth and services charge was offset by the savings in not having to hire a guard service. Nearly 12% of the annual lay-up berth cost was saved, with the added advantage of having shipyard support, crane service, a superior berth from a mooring and fendering standpoint, and superior weather protection.

It is common for laid-up vessels to either retain senior sea-going engineering staff or to

employ shoreside engineers who maintain the ship, with daily, weekly and monthly inspections, rotations of machinery, electrical insulation resistance (megger) readings, etc. As U.S. crewed vessels, the estimated cost of retention of the four (4) senior sea-going marine engineering staff for salary, benefits and food stores would run about $2,500 per day or $912,500 per year per ship. Employing a shoreside manager (ex-chief engineer) and two shore based lay-up engineers together with 2 to 4 laborers and a secretary totaled a little over $500,000 per year. Maintenance schedules were developed with the conclusion that this shoreside staff working eight-hour days could manage the lay-up of two ships and, therefore, the cost would be approximately $250,000 per year per ship.

The maritime crew alternative gave a 24-hour a day presence onboard (the 4 senior engineers were assumed to live on board the ship) and would maintain a 7-day a week coverage of the ships, Under the shore lay-up management scheme, the ships would be unattended for 16 hours each day and on weekends and holidays. While a locked gangway entrance and shipyard gate with guard provided satisfactory security, the prospects of fire on board, flooding of a machinery space, adverse weather conditions and other on board emergencies needed to be addressed to satisfy owners/charterers and underwriters concerns and requirements.

An alarm system utilizing modern electronics, interfaced with ship's existing systems, records fire, flooding and other perils, and notifies the necessary staff and shipyard personnel via telephone for appropriate response. The addition of beepers for shore staff lessened the impact of having the "duty" where designated personnel were "on call" and had to remain at the telephone number programmed into the alarm system. The total cost for all hardware installed was about $12,000 for two ships. In nearly 3-years of lay-up, using this approach, the system has performed satisfactorily.

LAY-UP ROUTINES AND PRE-REACTIVATION WORK

Lay-up crews involved only in repetitive lay-up tasks, with no specific goals or schedule, tend to grow inefficient and lose initiative. As it was clear that some pre-reactivation work had to be carried out, as discussed previously, the decision was made to hire additional staff, and to integrate lay-up and pre-reactivation tasks. An example of a portion of the 1994 work plan is shown as Figure 2, often referred to as a "GANT" chart, which gives start and stop dates for tasks and is designed to make the best use of labor and weather. Figure 3 shows projected manpower allocation for engineers to carry out the 1994 work plan, a similar chart is also utilized for laborers. Manpower that is over-allocated is either rescheduled or additional personnel are brought in. Because of weather, work usually peaks in the summer and fall. However, as a large amount of outside blasting and painting is to take place in the fall of 1993, other deck work is going to be suspended due to work conflicts.

Weekly meetings are held on board with management and staff to review progress, tool requirements, equipment status, spare parts levels and consumable requirements. Monthly budgets have been established for labor and supplies. Worker productivity has been maintained at a high level with substantial progress made on pre-reactivation work items. The majority of cryogenic system work is being carried out by trained, in-house staff, lessening the need for outside contractors and, thereby, reducing overall cost while still maintaining a high degree of quality.

RECOMMENDATIONS FOR OTHER LAID-UP VESSELS

The lessons learned on the lay-up/reactivation process of the subject LNG carriers may be applicable to other laid up vessels as follows:

Planning.

Project planning can be extremely beneficial to managing ships in lay-up. Because a schedule, with milestones, is created, and progress can be tracked, management and worker efficiency remains high, as the schedule and milestones are met. By reviewing the lay-up in the context of an overall plan, problem areas can be discovered early, before reactivation begins, and corrective actions taken. The inevitable schedule changes can be more readily accommodated, and the "what if" questions with regard to reactivation can be answered with more accuracy. Ultimately, this will reduce the cost of reactivating the ship.

Where more than one operator or shipyard

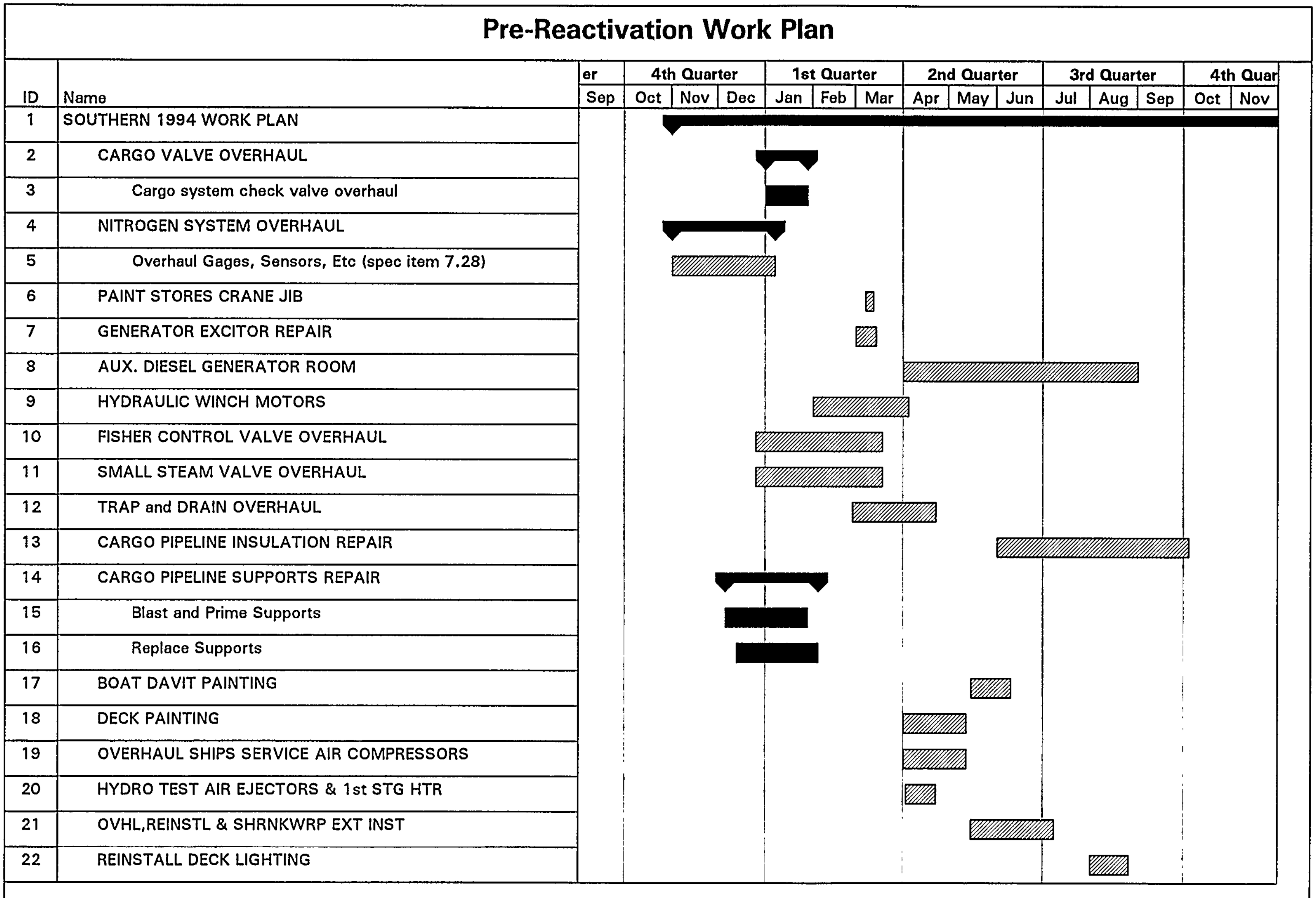
Pre-Reactivation Work Plan
ID
Name
er
4th Quarter
1st Quarter
2nd Quarter
3rd Quarter
4th Quar
Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov
1 SOUTHERN 1994 WORK PLAN
2 CARGO VALVE OVERHAUL
3 Cargo system check valve overhaul
4 NITROGEN SYSTEM OVERHAUL
5 Overhaul Gages, Sensors, Etc (spec item 7.28)
6 PAINT STORES CRANE JIB
7 GENERATOR EXCITOR REPAIR
8 AUX. DIESEL GENERATOR ROOM
9 HYDRAULIC WINCH MOTORS
10 FISHER CONTROL VALVE OVERHAUL
11 SMALL STEAM VALVE OVERHAUL
12 TRAP and DRAIN OVERHAUL
13 CARGO PIPELINE INSULATION REPAIR
14 CARGO PIPELINE SUPPORTS REPAIR
15 Blast and Prime Supports
16 Replace Supports
17 BOAT DAVIT PAINTING
18 DECK PAINTING
19 OVERHAUL SHIPS SERVICE AIR COMPRESSORS
20 HYDRO TEST AIR EJECTORS & 1st STG HTR
21 OVHL,REINSTL & SHRNKWRP EXT INST
22 REINSTALL DECK LIGHTING

Figure 2

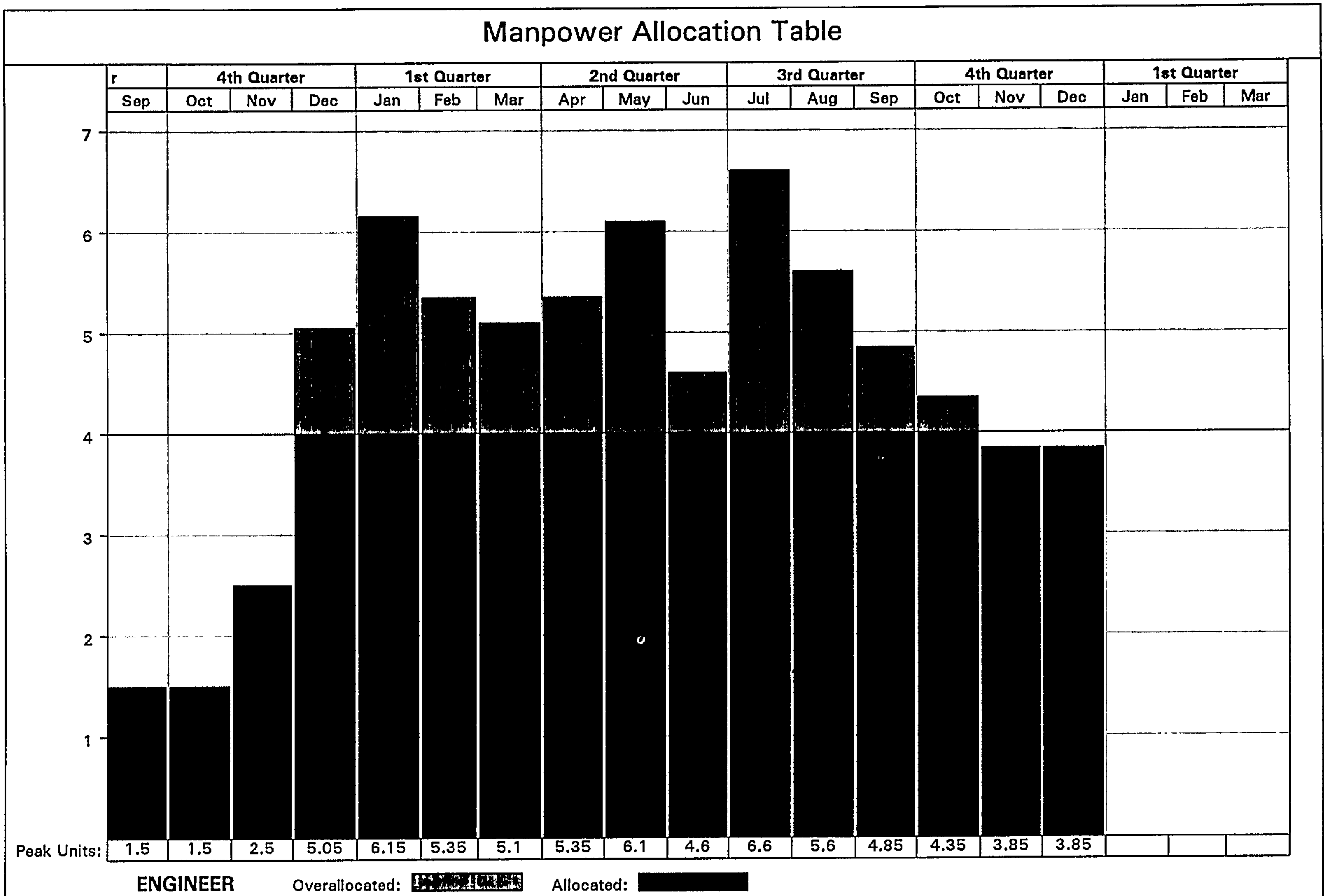
Manpower Allocation Table
r
4th Quarter
1st Quarter
2nd Quarter
3rd Quarter
4th Quarter
1st Quarter
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
7
6
5
4
3
2
1
Peak Units:
1.5
1.5
2.5
5.05
6.15
5.35
5.1
5.35
6.1
4.6
6.6
5.6
4.85
4.35
3.85
3.85
ENGINEER
Overallocated:
Allocated:

Figure 3

may be involved in the lay-up and reactivation of an RRF vessel, a common, computer-generated work plan provides needed continuity and documentation not available otherwise.

Drydocking.

There is a diminishing availability of drydock space in the U.S to accommodate medium to large size vessels, Reference 1 shows only 10 commercial shipyards on all coasts with substantial drydock facilities. Most East Coast yards require 6-12 months notice for any drydocking, and cannot afford to displace regular repair customers in order to accommodate the two, back to back, 25-day drydockings that would be required for delivering the subject LNG carriers on the desired in-service date. Therefore, long-term plans for reactivation may have to be tied to a specific drydock date, with changes in the reactivation schedule moving forward and back as necessary to meet that date.

For RRF vessels, drydockings should be carried out when required rather than seeking waivers for delay of drydocking until a vessel is reactivated. Ablative type bottom coatings should be applied to laid up vessels. One of the subject LNG carriers has an ablative bottom coating. It has been in the water for 13 years and to this day has no permanent fouling. Her sistership, moored alongside for the last 13 years, with a conventional anti-fouling paint, is heavily fouled. With the use of ablative anti-fouling bottom coatings, drydockings for RRF vessels might be scheduled based upon time in service, as opposed to fixed intervals between drydockings.

Major Machinery Overhaul.

A lay-up period is definitely a good time to conduct major machinery overhaul. Recognizing that all RRF ships must be ready in a limited number of days, major machinery overhauled should be conducted on a staggered basis so that only a certain percentage of the RRF fleet is in machinery overhaul condition at any one time and, therefore, has a longer reactivation time. Instead of categorically purchasing all spares needed for overhaul of equipment in service, it is better to open and survey the equipment in lay-UP and make specific purchases in a timely, cost effective manner. Often, equipment with worn parts, such as pump internals, is better off being repaired with new, long life synthetic materials than with "original equipment" replacement parts.

System Testing.

Frequently a ship in lay-up status for a long period has poor system readiness when reactivation is started. When there is a short time available to reactivate, especially with RRF ships, great sums of money are spent on expedited materials, round-the-clock labor and increased management. The question is always asked "Why weren't the problems and deficiencies known before?" Thus, in addition to regular lay-UP activities, critical systems need to be tested, run and/or cycled routinely, and repaired as necessary. Fluid systems that are preserved by coatings, treatment or D-H should be visually checked, but any active system with fluid in it, such as steering gear, main engines, etc. should be operationally tested at regular intervals. The results of these tests can then be integrated with the lay-up management plan, and resources allocated so that the ship will be able to be reactivated in the time frame and budget allocated.

CONCLUSION

Experience with the lay-up and reactivation of LNG carriers has shown the importance of applying project management techniques to vessel lay-UP. When evaluating the cost of vessel lay-up, overall costs including the cost of reactivation should be included. Reducing up-front lay-up costs can dramatically increase reactivation costs and the ability to meet required delivery schedules, negating all perceived benefits of the reduced lay-up costs. Project management techniques also enable better utilization of available lay-up manpower, further reducing overall costs.

REFERENCES

1) Report on Survey of U.S. Shipbuilding and Repair Facilities, U.S. Department of Transportation, Maritime Administration.

The National Shipbuilding Research Program
1993 Ship Production Symposium
Sponsored by the Hampton Roads Section SNAME

Laser Welding Analysis and Experiments

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ABSTRACT

A “Seamless Engineering” approach for mechanical design and laser welding manufacturing combines a method for welding analysis with a method for stress analysis through the development of radiant heating models for use in a nonlinear finite element computer program.

Experiments were performed welding steel plates, using a five-axis Computer Numerical Controlled (CNC) work station to translate welding specimens under a 5-kilowatt $C0_2$ laser. Thermocouples installed near the weld seam were used to measure the transient temperature field during welding. The measured temperatures were compared to the analytical predictions, and the welds were sectioned so that predictions of properties in the heat-affected zone could be compared with experimental data.

This paper presents analytical results using classical methods of analysis and includes solutions for temperature fields, heating and cooling rates, and metallurgical properties in heat affected zones.

INTRODUCTION

Computer-Aided Design (CAD), Computer-Aided Engineering (CAE), Finite Element Method (FEM), Virtual Reality (vR), Numerical Control (NC), CNC, Computer-Aided Inspection (CAI), and Cornputer-Aided Machining/Computer-Aided Manufacturing (CAM): These are the approaches to design and manufacturing that will propel the United States into preeminence in the 21st century global economy. These technologies emerged in the 1980’s and now permeate most of the design process in naval weapons, launchers, and ships. America has led the way.

If our competitiveness in the next century can be assured, it will be through applications of computers to the demands of the marketplace through these technologies.

In the area of naval weapons, the most significant pioneering application of the FEM was the design of the MK 104 dual thrust rocket motor (DTRM) for the SM-2 Block 11 Standard Missile (1 and 2). This was followed by design of the Block IV missile, which employs a separate booster motor. For Block IV, detailed FEMs were used for designing the rocket motors, fins, and a thermal protection system for aerodynamic heating.

In missile launcher design, the MK 26 Guided Missile Launching System (GM LS) arrived too soon to benefit from a FEM stress analysis. However, the launcher was even tually modeled to improve the system’s ability to withstand underwater shock. The MK 41 Vertical Launching System (VLS) was modeled very early in the design process to meet underwater shock requirements. The FEM was used extensively in the design of the VLS canister for Block IV. The most significant advance was the mathematically coupled analysis and concurrent design of both the canister and the missile. In both the missile and launcher areas, the design process and manufacturing processes are also making extensive use of computer-aided design and drafting (CADD).

In the area of shipbuilding, large FEMs with many thousands of degrees of freedom

were used in the mechanical design of the Spruance Class Destroyer (DD 963). The DDG 51 class design was a milestone in that all aspects of the design process were done with CAD, such as drawing generation, analysis, information management, configuration control, and interference detection.

A stress analysis for the aft deck house (3) was completed using the database and the FEM. The structural design of the TAGOS-19 Small Waterplane Area Twin Hull (SWATH) ship was completed with the FEM (4). The twin hull presented challenging design problems resulting from prying, shear, and torsional loads not present in monohulls. Furthermore, TAGOS-19 class ships are now being built from drawings in a numerical database. Extensive use of VIVID®,1 a computer program that allows an architectural "walk through" of a ship using virtual reality, was used in the arrangement of the Sea *Wolf* submarine.

In the same time period in which the CAD and FEM technologies emerged, CNC machining and robotics became commonplace on shop floors throughout the world. Boeing and Giddings & Lewis are now building 777 aircraft wings, four at a time, on a CINC workstation 88 m (290 ft) long, 21 m (70 ft) wide, and 2-1/2 stories high (5).

The next frontiers of computer-based engineering are nicknamed "concument" and "seamless." Concurrent means the simultaneous application of computers to several areas of the development process. For example, in order to minimize the time taken between the emergence of a concept and the introduction of the item to the marketplace, the design team includes production engineers so that the most producible and least expensive product results.

Some concurrent processes do not involve drawings on paper; for example, in the design of a pump and impeller (6), the internal geometry was determined through fluid flow calculations in a geometrical database in a CAD system. When the geometrical design was complete, another computer generated tool paths for a CNC mill that manufactured the parts; paper drawings were not used at either stage. Finally, rather than a dimensional inspection of the parts to assure conformance to drawings, the "as built" geometry was determined by measurement probes on a CAI station. The "as built" geometrical data were used as input to a final fluid dynamics calculation to see if the pump using the manufactured parts would meet performance criteria; again, drawings were not required. This smooth passage from step to step in design, development, and manufacturing, using a shared database at each step, is the essence of "seamless" engineering.

This paper describes a two-year effort at the Naval Surface Warfare Center Dahlgren Division (NSWCDD) to build a "seamless" technology for designing steel parts for assembly by means of laser welding with CNC workstations. The FEM is used in the stress analysis during design and to guide the final material selection and thickness. The same finite element computer database and software is then used to design the manufacturing process; i.e., laser beam on-off schedule, beam power, speed of welding, and tool paths. Just as stress analysis and post processing provides the mechanical designer with a visual representation of the stress field, the heat transfer analysis provides a means for visualizing the heat affected zone, metallurgy, and manufacturing process. The focus of the study has been on parts of sizes commonly found in missiles and launchers, which are compatible with the power available from the laser and the capacity of the five-axis NC workstation. However, with additional effort, the technical approach could also be applied on a larger scale to shipbuilding.

Three technical sections follow. The first technical section discusses classical, closed form analysis of the laser welding process and prediction of material properties. The next section discusses modeling the laser welding process with the FEM. The third technical section discusses the experiments conducted to determine effective thermophysical properties and to verify the accuracy of the welding process calculations. Finally, some potential applications of the laser welding process are shown in missile, launcher, and ship design.

1 Developed and owned by Newport News Shipbuilding

CLASSICAL MATHEMATICAL SOLUTION

The basic closed form mathematical model of the laser welding process is based on the “Rosenthal line source model.” The solution was discovered by Rosenthal (7) in 1946. The model assumes a uniform line source of heat moving at constant speed in a thin plate. The moving line is perpendicular to the plane of the plate (when viewed from above, the line source looks like a point moving on the surface of the plate). When expressing the source strength in terms of laser power and absorptivity at the date,the formula is

$$T(x,y,t)=T_o+\frac{AI}{2\pi hk}e^{-\frac{v}{2a}(x-vt)} \qquad (1)$$

$$K_o\left(\frac{v}{2a}\sqrt{(x-vt)^2+y^2}\right)$$

where

- To = initial plate temperature (c)
- A = absorptivity
- I = laser power(W)
- h = plate thickness (m)
- k = thermal conductivity (W/m K)
- v = beam travel speed (m/s)
- a = thermal diffusivity (m^ 2/s)
- x = distance in direction of beam travel (m)
- Y = distance from weld centerline (m)
- t = time (s)
- Ko = modified Bessel function of the second kind

Here it is assumed that the thermophysical quantities *k* and a do not vary with temperature. The plate is infinite in extent, and the speed of welding, v, is constant. The plate thickness and the intensity are constant. The resulting solution is pseudostationary, i.e., the temperature field always looks the same to an observer moving at speed v with the laser beam. The solution is mathematically mgorous, and the Bessel function can be evaluated with high precision; however, if there are significant violations of any of the above assumptions, results must be used cautiously. In general, the Rosenthal solution has been found to be very valuable in understanding the welding process it was used as a starting point in designing simple processes and as a check for finite element calculations.

The classical Rosenthal solution has recently become more useful due to advances in computer methods. Figure 1 is a temperature plot obtained by loading the Rosenthal solution into a commercial software package. The operator can readily change any of the parameters in the basic formula and can manipulate the object to provide any view desired.

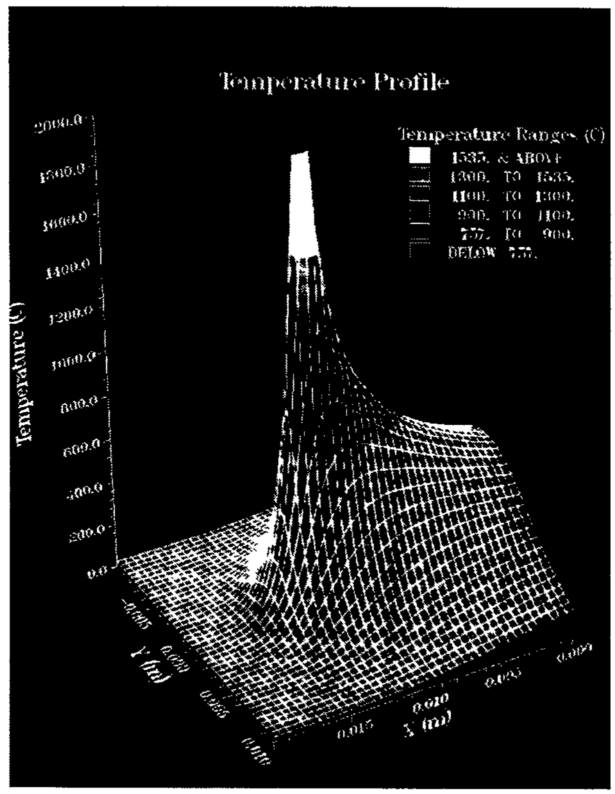


Figure 1. Temperature profile

Heating and cooling rates, important to metallurgy, can be obtained by differentiating Equation (1) with respect to time. Figure 2 is a plot of the heating rate. The heating rate is highest directly in front of the beam and lowest (large negative values, indicating cooling) immediately behind the beam.

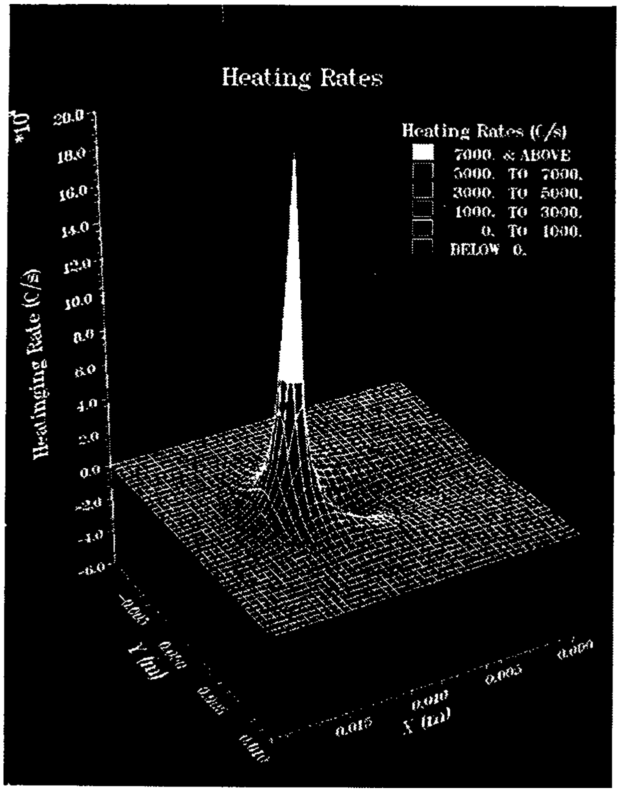


Figure 2. Heating rate plot

The computer calculus program "Mathematical" was used to differentiate Equation (1) with respect to the spatial coordinates to construct the temperature gradient field. The resulting formulas for the gradient field involve additional Bessel functions (the chain and product rules applied to Equation (1) produce large messy formulas). The gradient field of Equation (1) is the heat flux vector and shows the direction of heat flow away from the weld. A plot of the gradient field is shown in Figure 3. There is a tendency for crystal growth along the gradient field lines, which allows a computer prediction of the micro-structural orientation in the fusion zone.

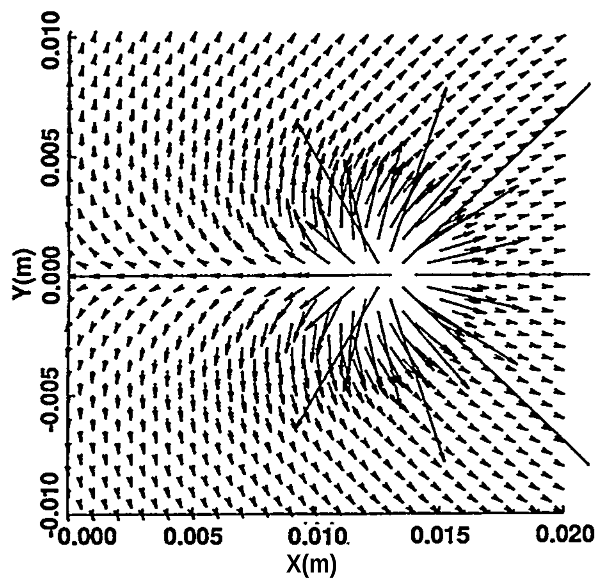


Figure 3. Thermal gradient vector field

Hardness and yield strength for laser welding of steel can be predicted using the above computer analyses to generate a set of temperature-versus-time plots for points of interest in the material. The analysis follows the approach of Metzbower (8). The "carbon equivalent" for the material is first computed from the formula,

$$Ceq = \%C + \%Mn/6 + (\%Cr + \%Mo + \%V)/5 + (\%Cu + \%Ni)/15 \quad (2)$$

Here the alloy elements symbols have the usual meanings. The volume fractions of Martensite, Bainite, and ferrite/pearlite are then given by

$$\begin{aligned} Vm &= 1 - \exp\{-0.69' [St/Stm]^2\} \\ Vb &= 1 - \exp\{-0.69^* [St/Stb]^2\} \\ Vfp &= 1 - Vm - Vb \end{aligned} \quad (3)$$

Where St is the time it takes at the point of interest to cool from 800°C to 500°C, and the half times for Bainite and Martensite to transform, S_{tb} and S_{tm}, are computed from

$$\log(S_{tb}) = 8.84\,Ceq - 0.74$$
$$\log(S_{tm}) = 8.79\,Ceq - 1.52 \qquad (4)$$

Figure 4 is an overlay of a temperature-versus-time computer solution plotted on an Aerospace Metals Handbook I-T diagram. The I-T diagram gives a qualitative prediction of the crystalline structure, and the computer calculations with the above formulae give a precise quantitative prediction of the metallurgy. Additional formulae are available for predicting the yield stress and hardness, once the metallurgy is known.

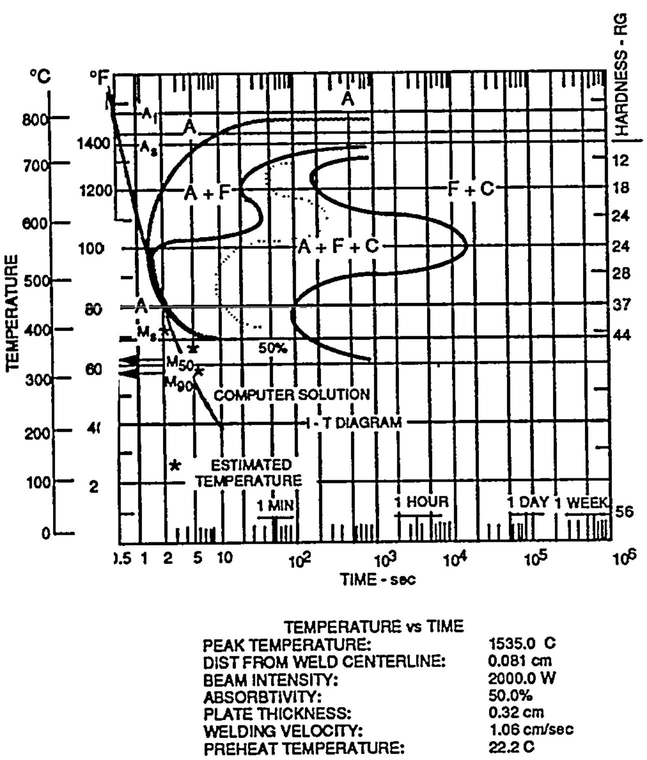


Figure 4. Temperature vs time overlay

In summary, given the assumptions of constant material properties, thickness, speed of welding, and beam power, the above formulae allow prediction of the temperature field during welding, the resulting metallurgy, and other material properties required for design. The calculations are quick and inexpensive on modern computers equipped with the proper software.

FINITE ELEMENT ANALYSIS (FEA)

This section discusses the FEM approach to laser welding. The finite element approach is an alternative that has the potential to overcome all of the limitations of the above classical method for real materials and variable geometries. Furthermore, the finite element method has the ability to use the same numerical database as the stress analysis and computer drafting of the final design.

The analytical solution described previously is only valid under the following restrictions

1. Infinite flat 2-dimensional (2-D) domain
2. Constant negligible thickness
3. Constant material properties (no spatial or temperature dependence)
4. Constant velocity source
5. Straight line weld path

These limitations greatly restrict the solution's utility for practical application to typical welding operations. Other analytical solutions are possible, using various moving sources based on a singularity integral approach, which may remove some of the stated restrictions. In general, all of the resulting formulations provide point solutions that require fairly expensive special function evaluations at each material point for each time at which temperature is desired. As a result of this expense, a numerical approach was sought that would provide the full simulation required to optimize the welding process, while still remaining cost and time effective.

Simple analyses were carried out using a finite difference thermal network formulation – a transtinite element formulation in which the conduction solution was obtained in the Laplace domain and then inversely transformed to provide the temperature-time history and a more general finite element solution using the ABAQUS™ program. A decision was made to perform the remainder of

history and a more general finite element solution using the ABAQUS™ program. A decision was made to perform the remainder of the simulations using this FEM program, based on its already widespread availability throughout the Navy, its generality for stress-displacement analyses as well as thermal analyses, and its high level of integration within the overall CAD/ CAE/CAM process.

This approach allowed for modeling complex 3-D simulations with variable beam speed and spot size; curved welds; and temperature dependent material properties, thus eliminating nearly all of the restrictions described earlier. The identification of the proper temperature dependent material properties presents a considerable challenge, however. Also, the severe spatial and temporal non-linearities produced when using variable thermal properties significantly reduce the integration step size, and greatly increases the cost of the analysis. Therefore, a methodology (described below) was developed to obtain a representative set of constant properties based on the specifics (thickness and diffusivity) of the problem being solved. Also, while this approach permits the inclusion of radiation and both free and forced convection (i. e., resulting from shielding gas flow); it also greatly complicates the analysis. For the example cited here, these effects were ignored.

The process of using a CAD system through analysis modeling and simulation to validate a weld process specification, along with some lessons learned, is described below. The typical process involved the use of Pro-Engineer" as a design modeler. The geometry of the problem was then transferred to PATRAN, a modeling program, for stress and thermal analysis. This generally involved subdividing the design-modeler derived surfaces to control mesh density and to define weld path, followed by the generation of hyperpatches to describe the volume of the structure. Then by proper manipulation of the meshing controls, a finely graded mesh is produced. Figure 5 illustrates such a mesh.

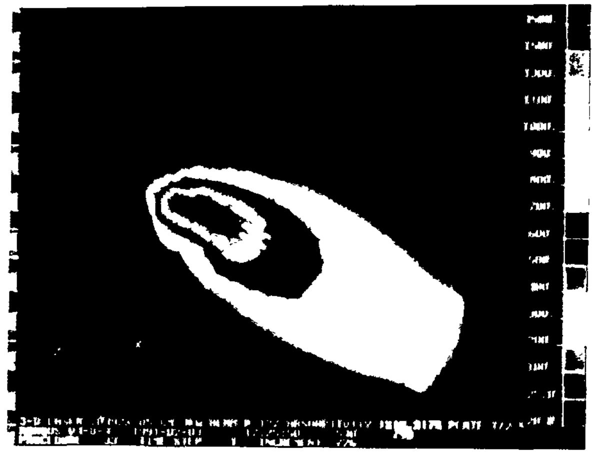


Figure 5. Finite element solution for a source moving along the surface of a weld specimen

Several observations can be made to point out lessons learned regarding the compromise between solution accuracy and cost. In a few early calculations with 2-D shell models, with through-thickness integration points, great efficiency and acceptable accuracy were obtained. However, the elements were found to be incompatible with some of the post-processing and stress analysis functions. (The mesh shown in Figure 5 is composed of DC3D8 linear hexahedral elements.) Several rules of thumb were developed to guide in meshing. One of these rules is that symmetry or no-flux boundaries need to be exploited. Also, for the power and speed settings typical of laser welding processes, it was found that in the direction transverse to the weld path, a mesh dimension of approximately two weld thicknesses was sufficient to approximate an isothermal boundary.

The model shown simulates a constant power butt weld pass on a 25.4 mm (l-in.) square by 9.5-mm (0.375 -in.) thick flat plate. Here the far lateral edge is 12.7 mm (0.5 in.) from the weld, which results in approximately a 5°C (41°F) temperature increase. The mesh should be highly graded from a fairly refined uniform mesh in the vicinity of the weld to a very course mesh at the lateral boundary. In this example, the small element dimension is chosen as a cube with a face area equal to the area of the laser beam spot size. The symmetry condition at the weld line results in this element being split in half; this split cube is

element being split in half; this split cube is repeated laterally one step, followed by the full cube, and then the grading is carried out to produce one element through the thickness at the isothermal boundary.

A fair degree of judgment and expedience is used to arrive at a “good looking” mesh. This mesh is then swept along the weld path to produce a full 3-D model. For butt welds on thin, topologically uniform 2-D structures (i.e., flat, cylindrical, etc.), a no-flux or symmetry boundary condition can be assumed at the weld line even though the geometry is not symmetrical. Thus, the two sides of the weld can be analyzed separately. In actual practice, it is often only necessary to analyze one side of the weld.

For branched structures (i.e., T welds), all sides of a structure must be modeled. When filler metal is not used, the problem can be greatly simplified by allowing the mesh to be connected even before the beam has passed. In most cases, this actually produces surprisingly small error. A characteristic element face area equal to beam spot area is chosen to simplify the specification of the energy incident on the weld zone and the propagation of the beam along the weld path. The critical feature is that the mesh is invariant and regular along the weld. After higher resolution meshes were investigated, it was concluded that the approach described above provided a good compromise between accuracy and computer costs.

The thermal input is applied as a surface heat flux on the row of elements adjacent to the weld path. The magnitude of the heat flux is obtained by assuming the beam power is uniformly distributed on the beam spot, and that the absorptivity is invariant with temperature. These approximations and the distortion of the energy distribution into a square greatly simplified the problem specification without introducing significant error. The actual energy distribution is annular; however, detailed simulations showed that for a dynamic welding pass, the energy could be uniformly smeared over a square with area equal to the beam area. Figure 5, shown previously, exhibits a finite element solution for a source moving along the surface of a weld specimen, Figure 6 shows the temperature at various positions on the material.

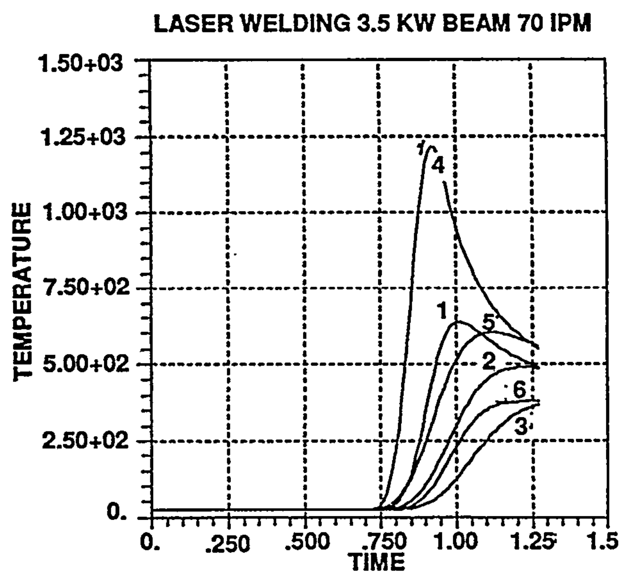


Figure 6. Temperature at various positions on the material

The numerical value of the absorptivity can be approximately calculated from the Stefan-Boltzman constant times the emissivity times the equivalent beam temperature to the fourth power, divided by the laser power setting.

$$A = \sigma\, \varepsilon\, T^4 / I \qquad (5)$$

A more practical empirical approach based on a simple calibration test will be described below.

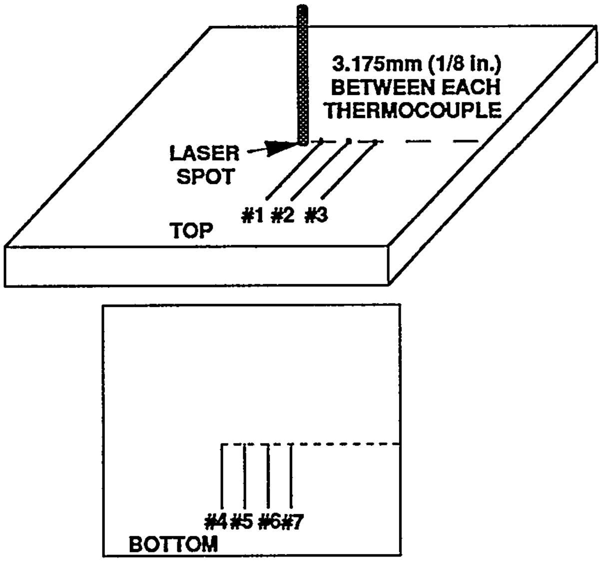
To simulate the beam motion, a schedule of heat flux is derived for each element such that it rises from zero, when the edge of the beam is projected to first enter the element domain, to its maximum value, when the spot is centered on the element, and then falls to zero when the spot edge exits the element. The adjacent elements are heated in a consistent manner such that the total heat flux to the structure is constant, and a particular element exposure is twice the time it takes the beam to traverse the characteristic element dimension. Beam speed can be varied by altering this traversal time as a function of time; also, beam power can be varied to simulate beam defocusing, which is used to reduce incident energy when required to avoid burn-throughs.

This approach provides direct analogs to the process parameters used by a manufacturing engineer when constructing a CNC program: namely, beam path, beam speed, and standoff (when standoff equals the focal length for full power incident on the focused spot area). The simulation results are then studied to predict maximum temperatures, back face temperatures, fusion zone, heat-affected zone (HAZ), metallurgical phases, and hardness variations. These functions are provided as post-processing options and can be visualized using the modeling program as fringe plots or time histories. Computer generated animations can also be videotaped to provide a level of data abstraction and fusion that is helpful in developing a “feel” for the welding process. With this type of feedback, a manufacturing engineer can vary parameters in the process schedule in a systematic fashion. Additional simulations provide further feedback, which makes it possible to quickly arrive at the final process.

The technique described above provides a straightforward method to accurately simulate laser butt welds (without filler metal or gas shielding), heating, heat treating, and cutting. Analyses involving other weld geometries, forced convection due to shielding gas flow and filled welds, are somewhat more complicated; however, the FEM provides sufficient generality to adequately handle these complications. Filler metal can be added in a conceptually straightforward manner through the use of the user element capability.

As the complexity of the simulation increases, difficulty in correlating the analysis to the experiment increases. This is as much an effect of the proliferation of unknown (unknowable) parameters in the problem as it is the complexity of the physics being modeled. The final test is in how effective the computer simulation aids a manufacturing engineer in developing a process specification. In practice, most of the tasks presented can be modeled adequately as a straightforward conduction problem, neglecting much of the complicating physics, as long as one or two empirical variations are run for calibration purposes. These empirical runs are made on small representative coupons of the correct material and thickness. This eliminates the risk of damaging expensive, few-of-a-kind, complex components or overheating pyrotechnic ordnance. Once a validated process specification has been developed, welds can be made with high confidence and safety.

A fairly rigorous calibration procedure was developed as a formalization of this coupon testing. A specimen of the parent material was instrumented with seven thermocouples radiating from its center at distances of 1, 2, and 3 beam diameters on the top, and 0, 1, 2, and 3 beam diameters on the bottom (Figure 7). The plate was then heated by a square wave pulse of laser energy directed at the center of the top surface for a predetermined duration and power setting. Once the plate cooled, exposure was repeated with a different power setting or different duration. Data collected from several tests were analyzed by a nonlinear least squares method to fit a closed-form singularity integral solution. Model parameters obtained were then proven out by a detailed FEM simulation of the experiment.



#4: DIRECTLY BELOW BEAM SPOT

LASER POWER: 500W
PULSE DURATIONS: 1,2, AND 4 sec

Figure 7. Thermocouple placement

This system identification procedure provides approximate estimates of the physical parameters required for the simplified FEM described above. Essentially, it is a process of linearizing the analysis for a temperature range of interest, which may be dependent on the intent of the analysis. The parameters could also be chosen so that the error is minimized in some least squares fashion over the entire domain. A solution of this type would over-predict peak temperature somewhat, but would have lower error at the far field. The choice of approach must be based on the desired end result.

For HAZ or fusion zone predictions, the error should be minimized for the temperature range and distance scale expected. For peak backface temperature predictions, the model should be tuned differently. A different analysis run is required for each model change, but the aggregate run times are still much less than the full nonlinear analysis. The temperature dependent property data available in the literature are spotty at best; some sort of tuning will always be required. This approach greatly reduces the cost of the FEA, uses a simple test procedure, and requires only a small material coupon. This procedure has been very useful for determining the model parameters.

LASER WELDING EXPERIMENTS

The 5000-watt CE5000/LPC8 $C0_2$ laser is a computer-controlled laser processing system comprised of a high voltage power supply, lasing chamber, and CNC workstation. The workstation is a five-axis machining center driven by an Allen Bradley 8400MP controller, which also controls the laser during program execution.

NSWCDDS laser is capable of delivering a beam of up to 5000 watts to the workstation. The beam is a continuous nonpulsed beam with a 3-inch annular mode; i.e., doughnut shaped. Once the beam reaches the workstation, it can be focused using one of two focusing heads.

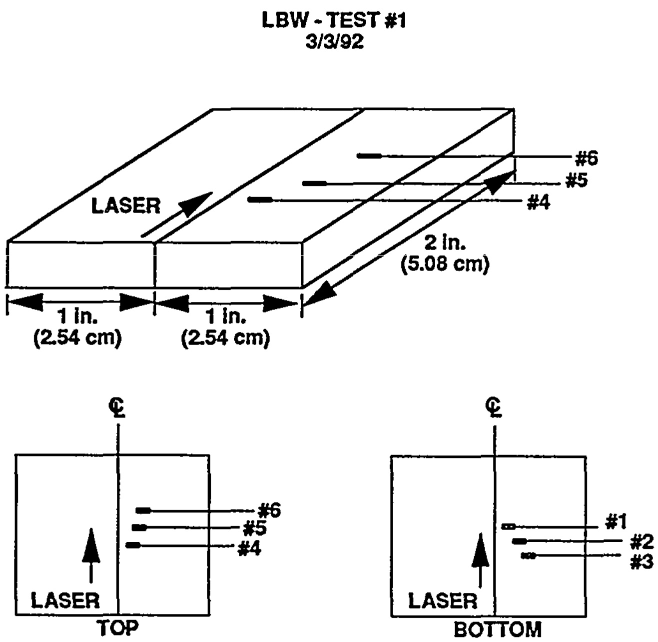
One of the focusing heads uses a conventional parabolic mirror, or a parabolic integrator mirror. The second focusing head contains a conventional parabolic mirror, which can scan up to a l-inch long line as fast as 20,000 cycles per minute.

The scanning focusing head is used for surface heat treating or cladding. In this use, a focused beam of 1.524-mm (0.06 -in.) diameter is rapidly scanned or dithered at a controlled rate as the part is moved under the laser head.

The other focusing head is used with the solid parabolic mirror for welding or cutting. With this mirror, the beam can be focused to a diameter of 1.524 mm (0.06-in.). The integrator mirror is a sectioned parabolic mirror with each section focused such that a 1%-inch square region is affected by the beam. The integrator mirror can be used for surface heat treating.

Laser machining is a noncontact type of processing; therefore, all setup fixtures are mostly used for positioning the parts under the laser, and for limiting movement of the parts due to thermal stress. The fixtures used are designed to assure repeatability of welding parameters.

All samples were made from %-inch 4340 steel sheets. The thermocouples used were OMEGA Chromel/Alumel ™ with a 0.127-mm (0.005-in.) diameter. The laser spot test used seven thermocouples spot welded to the plate as shown in Figure 7. The welding experiment used the configuration shown in Figure 8 (only one plate contained thermocouples). In both experiments, grooves of 0.127-mm (0.005 in.) were machined into the surface of the plate steel. The grooves were aligned such that one end of the groove could be used when locating the thermocouples.



WELDING PARAMETERS:
LASER POWER = 70% (3.5 kW)
WELDING SPEED = 70 ipm 2.963 cm/s)
AMBIENT TEMPERATURE = 70 F (21.1C)
PLATE MATERIAL = 4130 STEEL (INITIALLY ANNEALED)
PLATE THICKNESS = 1/8 in. (3.175 mm)

THERMOCOUPLE	DISTANCE FROM ℄ (mm)
1	1.52
2	2.27
3	3.20
4	1.02
5	2.03
6	3.05

Figure 8. Welding experiment configuration

The spot weld experiment was the simplest way to show that the experimental data and the classical/FEMs approximated each other. As explained above, the spot heating experiment can be used to obtain average material properties for finite element analyses. In this experiment, a beam of 500 watts was focused on the sample for 1 second. The test was repeated using 2- and 4-second intervals. A Data 6000 Digital tape drive was used to record all thermocouples. An analog-to-digital converter with a radio frequency (RF) filter was used in line with the thermocouples.

In the welding experiments, the focused laser beam was used to weld two plates together while recording temperatures. The laser beam was started when the plate was well away from the sample, then the plate was moved at a constant feed rate in a line that tracked the seam. The laser shut off once the beam moved off the sample. Starting and stopping the laser away from the sample assures that there is a constant beam power during welding. Beam powers of 2000 to 3500 watts with machine speeds of 50 to 70 inches per minute were used in these experiments. Figure 9 shows the results of one of the experiments.

The plots on Figure 9 also show the Rosenthal analytical solution and the finite element solution. The Rosenthal solution is readily computed for the exact thermocouple locations and shows good agreement with the experimental data. The finite element results need further explanation. These results show temperature-versus-time plots for finite element mesh points near the thermocouples, but not exactly at the thermocouple locations. For example, thermocouple location number 4 is on the top surface 1.0 mm (0.0394 in.) from the weld center line. The closest node is number 1437, which is 1.524 mm (0.06 in.) from the weld. The nearest node to the first thermocouple underneath is number 1409, which is 1.016 mm (0.04 in.) from the weld center line.

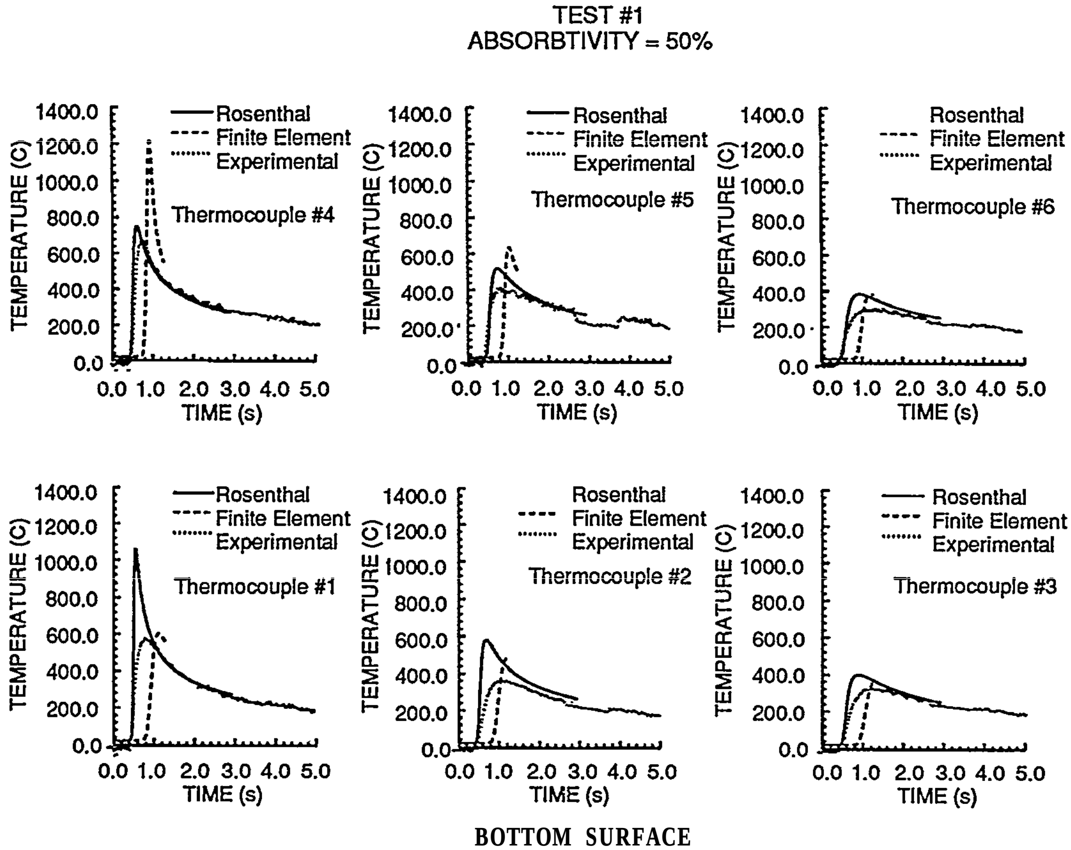


Figure 9. Temperature versus time plots from classical Rosenthal solution, finite element method, and experimental data

The Rosenthal solution does not take into account the variation of temperature with depth through the thickness of material. The heat source is from the top, so one would expect the Rosenthal solution to be higher than the bottom measurement close to the weld, and this is confirmed by the data. On the other hand, the finite element solution takes into account the heat flow in the thickness direction. The heating is from the top surface, hence, the high values in Figure 6 for location number 4, and much lower values for location number 1 on the bottom side. At the second location, a little over 2 mm (0.0788 in.) from the weld, the temperatures top and bottom are more nearly the same, as shown by curves 2 and 5. By the time the heat gets to the third location, the only difference in the two traces is a slower rise on the bottom side of the plate.

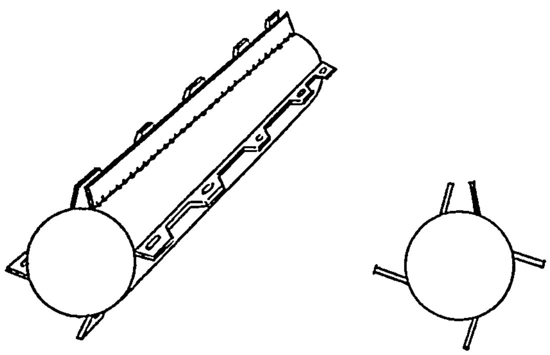
Another problem that occurs, especially close to the ~veld, is the thermocouples have mass and the leads are a heat sink, lowering the apparent temperatures. This is particularly true where gradients are strong and the transients are fast.

Finally, the general time phase different in the finite element results is due to a time base shift, not computational error.

After the experiments were performed, weld samples were sectioned and examined. The samples were polished and then etched using a 2-percent solution of nitric acid. The sample sections were examined for microstructure and microhardness. From microstructure photographs, the sizes of the actual weld melt zones and the heat affected zones were compared to the predicted analytical and finite element modeling, with good results.

FUTURE APPLICATIONS

The laboratory is presently pursuing three potential applications of the laser welding technology. The first application, nicknamed “Strip Clip”[2] (Figure 10), is an approach to building rocket motors (9). The second is a missile launching canister called the “Concentric Canister Launcher (Figure 11).” The third is the “Integral Ship-Weapon Module (Figure 12).”



ATTACHMENT OF LEFT FACING STRIP MANUFACTURING PROCESS - 5

Figure 10. Strip Clip approach to laser welding

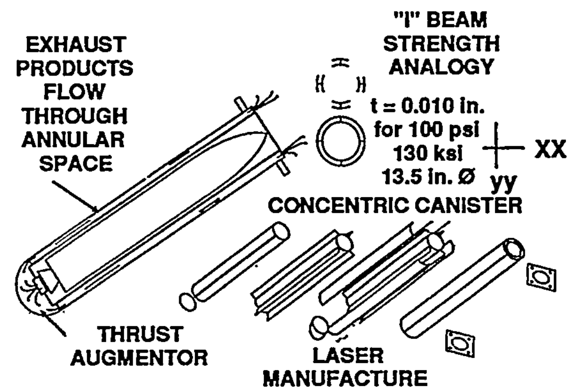


Figure 11. Concentric Canister Launcher approach

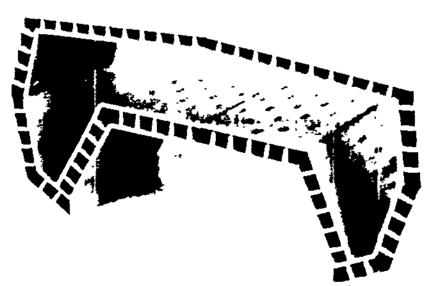


Figure 12. Laser-welded integral ship-weapon module

The present method of attaching the dorsal fins to the MK 104 rocket motor is by means of bolts passing through discrete fin clips. The "U" shaped clips, 216 per rocket motor, are presently welded to the chamber using 432 manual TIG welds on a preheated chamber. With laser welding, eight continuous strips are laser welded to the chamber on a CNC workstation. Only eight welds at ambient temperature are required on each chamber, Figure 10. The strips are then contoured and perforated by the laser in a cutting mode. Once set up, a complete set of attachments could be produced in only 20 minutes on a workstation, as opposed to the manual method that takes approximately two man days of manual welding.

The concentric canister launcher concept is shown by Figure 11. The concept was motivated by the Strip Clip rocket motor. The missile is fired from the inner cylinder or barrel. The inner cylinder supports the missile in handling and stowage, and guides it in initial flight. The missile exhaust flows into a hemispherical cup and is turned through 180 degrees along the axis of flight. The exhaust then flows in the annular space between the two cylinders. The same basic stress analysis approach is used as in the design of a rocket motor chamber. The manufacturing process is very close to the Strip Clip process, with the additional requirement to attach the outer cylinder. This can be done with petals, as shown in Figure 11, or by welding from the outside of a continuous cylinder, as explained below—using petals makes it easier to apply insulation to the annular space.

The integral ship weapon module is a concept for installing weapons in future surface combatants. The intent is to provide a fully stressed ship module for launching weapons. The weapon launcher becomes a structural part of the ship, rather than a plug-in item that fits through a heavily reinforced opening in the deck. The goal is to save weight, cost, and volume, thereby allowing a smaller, lighter ship with the same firepower as conventional designs. A ship module, of surface effect ship configuration, is shown in Figure 12. The model was built for demonstrating the welding and design approach. The design is a double hull with all plate construction. Plates are natural structures for finite element design. Virtually every finite element computer program has sophisticated and accurate plate elements. The laser welding process allows all the welding of the ribs to be done from outside the plate; i.e., the laser beam pierces through the plate from behind, then heats the rib, fusing it to the plate. The welding can be done continuously, as was done along the edges and at the center line, or intermittently, as along the ribs. Intermittent welds are obtained by turning the beam on and off while the parts are moving under the laser head. This process could also be used to attach the outer cylinder to the longer ones of the concentric cylinder launcher.

CONCLUSION

The rudiments of a "seamless engineering" process for design and production of laser welded structures have been demonstrated. Classical and finite element computer solutions of heating, cooling, and microstructure have been carried out. The calculations have been done in numerical databases that can also be used for stress analysis, printing out drawings, and development of CNC tool paths. Experiments, micrographs, and microhardness measurements have confirmed the computer methods. Several promising applications in the area of weapons, launchers, and shipbuilding were discussed.

ACKNOWLEDGEMENTS

The project was carried out as a part of the NSWCDD Independent Exploratory Development program. Four Dahlgren Division technical departments contributed. Mr. Robert W. Lowry obtained the laser, CNC workstation, and industrial computer. His technical contributions in planning the project and carrying out the first year's effort are also acknowledged. Mr. John W. Powers carried out the computer calculations based on the exact Rosenthal Solution and assisted with the experiments. Richard E. Miller and his staff designed the data acquisition system, installed the instruments, and processed the data.

REFERENCES

1. Raybern, D.A. and Williams, R.N., Stress Analysis Report for the EX-104 Rocket Motor Case (Dwg L5334009), Thiokol/Wasatch Division, Thiokol Corp., Report No. TWR-30481, Revision A., 8 December 1981.

2. Yagla, J. J., Rocket Motor Design for Underwater Shock, ASNE Day Technical Paper, May 1988. pp. 215-225.

3. Ayers, R. E.; Callahan, P.J.; and Kassel, B., "Application of a General Purpose CAD System in the DDG-51 Design Process," Naval Engineers Journal, May 1988, pp. 265-274.

4. Reilly, E.T., Shin, Y. S., and Kotte, E.H., "A Prediction of Structural Load and Response of a Swath Ship in Waves," Naval Engineers Journal, **May** 1988, pp. 251-264.

5. Murray, C.J., "Automation Comes to Airframes," Design News, 21 September 1992.

6. Meyer, Erich A., "Tooling for Impeller Castings Via CAD/CAM, " Naval Engineers Journal, May **1991,** pp. 269-277.

7. Rosenthal, Transactions of American Society for Mechanical Engineers, Vol. 68 (1946), pp. 849-66.

8. Metzbower, E.A., "Laser Beam Welding: Thermal Profiles and HAZ Hardness," U.S. Naval Research Laboratory, Welding Journal, Vol. 19, July 1990, pp. 272-278.

9. Yagla, J.J.; Lowry, R.W.; and Mears, O.L., U.S. Patent No. 5,106,034, Device and Process for Attachment of Parts to Rocket Motors, 21 April 1992.

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Commonality-Based Naval Ship Design, Production & Support

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ABSTRACT

The Naval Sea Systems Command (NAVSEA) began an initiative titled "Affordability Through Commonality" (ATC) in 1992. The effort's long-term goal is to improve the process by which the Navy, with industry's help, will design, acquire, and provide lifetime support for the ships required for national defense. The technical approach considers commonality to be a synergistic combination of the elements of modularity, increased equipment standardization, and process simplification. A division within NAVSEA (SEA 03R3) was created to coordinate efforts towards this fleet affordability goal, specifically to:

- identify and develop analysis tools for a commonality based process,
- assemble resources for initiating a decade-long task,
- develop a plan for a commonality-based approach to ship design, acquisition, and lifetime support and
- implement the plan into the mainstream of the Navy's way ofconducting business.

This paper provides an interim report on the ATC project's first funded year and the implementation progress of the first program to fully adopt commonality principles, the Advanced Surface Machinery Programs (ASMP), SEA 03Z.

INTRODUCTION

Rear Admiral Millard Firebaugh and Captain Robert Percival presented the ATC concept before the Ship Production Symposium last year (l). The ATC project office was established within the Naval Sea Systems Command in August 1992 with a charter to develop the necessary strategies, standards, designs, specifications, and procedures to provide the Navy the means to lower the costs of fleet ownership through the use of increased commonality. Commonality is defined as the synergistic combination of the three pillars of

- equipment modularization,
- increased equipment standardization, and
- process simplification.

The use of increased commonality in naval ship design and acquisition can lead to shorter design and construction times, maintain economical procurement quantities in the face of a reduced fleet construction schedule, improve shipbuilding quality control, and facilitate ship operation, maintenance, and upgrade. The goal of the ATC project is to build upon previous programs which fostered modularization, standardization and process simplification, and to work in conjunction with other current initiatives which support the goals of fleet affordability.

BACKGROUND

The ATC initiative was formulated in response to three issues that have emerged, or have become more prominent over the past several years with the decline of the Soviet military threat and the increase in global economic competitiveness. First, there is an affordability crisis that has been building for years, evidenced by rising naval ship costs. With the end of the Cold War, the defense budget is under steady downward pressure, and is likely to continue decreasing for some years. The decrease in the size of the fleet has significantly reduced the number of naval ship orders, causing corresponding unit-cost increases due to loss of production volume.

The second problem is the shrinking U.S. maritime

industrial base. There has been a historic problem with maintaining U.S. commercial shipbuilding competitiveness, with occasional periods of great activity and world leadership (notably World War II). Most recently, however, United States shipbuilding activity for large commercial ships has become nearly non-existent. The naval expansion of the 1980s obscured this trend to some extent with increased naval ship orders. With the current decrease in naval shipbuilding however, the number of competitive shipbuilders and supporting vendors is decreasing at an alarming rate.

The third issue that prompts consideration of commonality is the increased uncertainty in the national strategic situation. After decades of a relatively predictable threat, there is now considerable discussion in defining the maritime threat, how our defense should be configured to counter the threat, and what other threats might develop in the future. The uncertainty in this area increases the need for and value of flexibility in the design and operation of U.S. weapons platforms (2, 3).

Commonality Concept Description

ATC'S goal is to reduce the cost of ship acquisition and in-service support by reducing the cost and complexity of ship design, procurement, production, fleet introduction, and life cycle operations and support. This objective will be achieved through the use of equipment modularization, increased equipment standardization, and process simplification.

Equipment modularization is the determination of packaging and interface standards at the system level. This entails the joining of components into larger subassemblies in a way that enhances production efilciency, provides flexibility for in-service maintenance and upgrade efforts, and enables increased equipment standardization by grouping these components into reusable design elements. Ultimately, these modules are intended to be utilized across ship classes.

Increased equipment standardization is the reduction of the number of piece parts necessary to support the Navy. Standards, specifications, and design criteria will be developed for each family of common modules; the policy of increased standardization will be implemented in the development of these modules. The challenge will be to determine what unique requirements to impose and how much standardization to maintain in these module designs.

Process simplification includes the strategies, policies, and procedures to implement the following:

- Fewer, more standard system designs (Hull, Mechanical &Electrical [HM&E] initially, other systems as resources permit),
- Selective implementation of military specifications and standards,
- Procurement of equipment at the fleet level,
- Generic and engineered build strategies for each type of ship,
- Improved and efficient assembly of major equipment and systems,
- Increased parallel assembly and test of equipment and systems during ship construction,
- Fewer systems and less equipment to support (i.e., spares, training, etc.),
- Standardized, replaceable components and subassemblies to facilitate maintenance and modemization, and
- Use and reuse of digital data across discipline lines and across the boundaries of design, acquisition, production, and in-service engineering.

Thus, the processes to be simplified include ship design, production, logistics suppo~ and requirements definition. This simplification will depend upon the degree to which the concepts of modularity and standardization are adopted in the form of common equipment modules built to ATC standards, i.e., standard components packaged as larger subassemblies for installation and service in various classes of ships (Figure 1).

The output of ATC will be development of designs, standards, and procedures which reflect an architecture of “commonality” across the fleet at the sub-system level. The approach is to identify cost-drivers, determine the extent to which common modules and improved procurement practices can reduce the time and cost of the ship acquisition process, and create a plan of action for the development of appropriate sub-system designs, standards, and procedures. Criteria will be developed for determining the degree of standardization and modularization required for each major sub-system. Industry will play a major role in developing this plan of action.

Overview of ATC/ASMP FY93 Tasks

In the fiist developmental year (1993) of this multi-year process improvement task, both top-down systems engineering and detailed prototype engineering were initiated. Coordination and cooperation with the ASMP program office also continued from ATC'S 1992 study phase. Management of the ATC efforts was divided into the following categories:

- Design integration management,

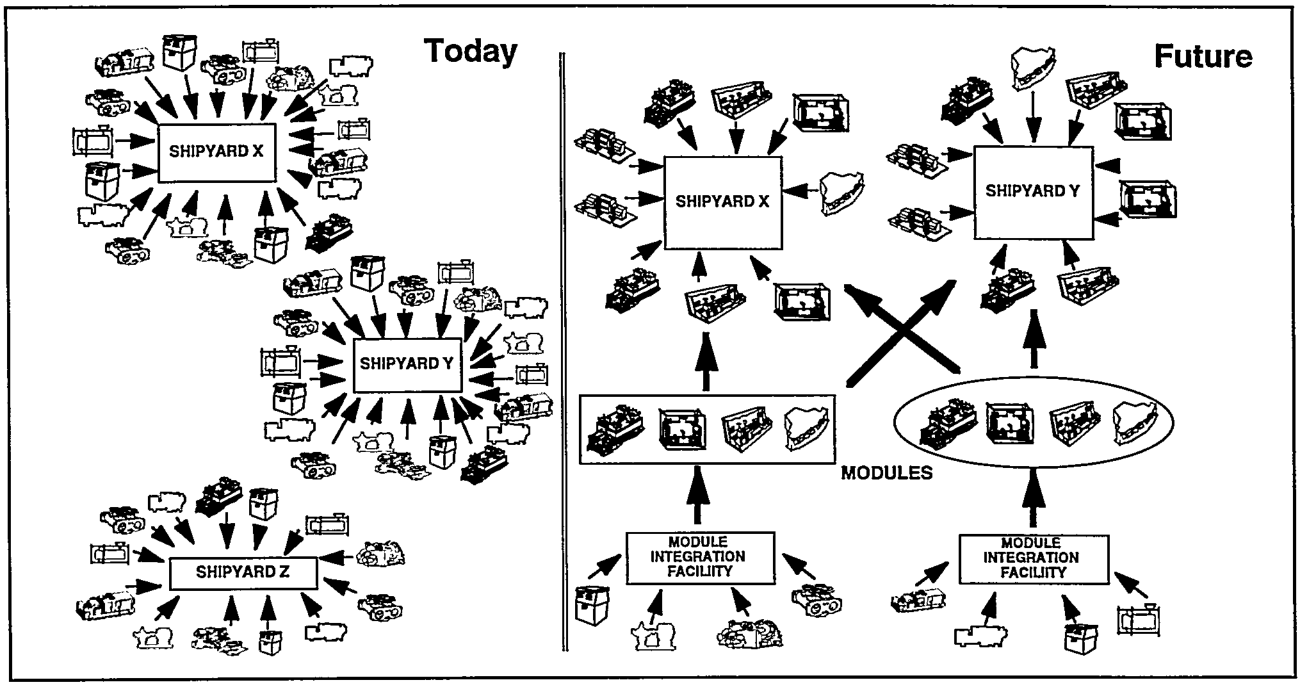


Figure 1. The Vision of Increased Commonality

. Cost analysis and model development,
. Plans and programs,
. Integrated logistics support and special projects,
. Hull and habitability systems,
. Machinery systems,
. Production processes,
. Combat systems, and, to be added in the future,
. Command, control, communications, computers and intelligence (C41).

Each task within these categories was prioritized for various levels of early funding. Each category has an Assistant Project Manager (APM) with intercategory coordination achieved through management team ofilce co-location and regular meetings of the full team. In addition to these efforts, the ASMP (whose representatives attend all ATC team meetings) administered the following tasks related closely to ATC goals:

Naval ship architectural studies characterize Integrated Power Systems (IPS) and identify associated machinery modules which support proposed combatant, amphibious and auxiliary ship concepts (Figure 2).

Commercial ship studies establish machinery system baselines for various commercial ship types in order to establish design-to-cost targets for comparable IPS systems and modules.

Costing tasks estimate costs to build, pre-test, and install machinery modules derived in naval ship architectural studies. It also includes the establishment and implementation of a formal life cycle cost model, which includes all costs associated with design, acquisition, construction, fleet introduction, and operating and support of IPS modules across the fleet (Figure 3).

IPS/pulse power integration studies characterize pulse power weapon support systems in terms of machinery modules.

The ASSET model update task updates the ASSET Ship Synthesis Model to allow rapid detailed evaluation of IPS modular machinery systems concepts for naval combatant and non-combatant ships.

There is a diverse range of disciplines and skills on the ATC/ASMP team, composed of government personnel (headquarters and laboratory), local support contractors, and geographically dispersed shipyards and suppliers. Some of the fiist year's efforts are reported to give a representative overview of the work being accomplished in the ramp-up year, work that will be continued and expanded upon in the out-years.

PRODUCT AND PROCESS IMPROVEMENT

Propulsion Systems

The IPS is **a** unified electrical power generation and management system serving all power requirements in naval surface combatant and non-combatant ships. Utilizing enabling technology advancements in permanent

Ship Type	Lead Award	No. in Class	Speed (kts)	Total SHP	No. of Shafts	Ship Service Load (KW)				Shock Rqmt	Data Source
						Shore	Anchor	Cruise	Mission		
SC-21	01	40?	28+	50,000	2	1800	2000	3650	3480	Yes	DDS Study 23 Apr 93
Amphib	96	12	23	40,000	2	4950	4950	5650	5850	Yes	LSD-41 LST-1179
Dry Cargo Shuttle	01	6	20	30,000	2	3275	4050	4450	5250	No	AFS-1 TAO-187
Repair	?	2	20	20,000	1	7650	8900	9500	21200	No	AD-41 AS-31
Sealift	00	40	24	60,000	2	2000	2050	3750	3650	No	SL-7

Figure 2. ASMP Target Ships

magnet materials and solid state power electronics, IPS consists of an architecture and a family of modules from which affordable, ship specific configurations can be developed for various applications. IPS incorporates use of Permanent Magnet (PM) Generators, PM Propulsion Motors and DC zonal electrical distribution, operating with the Standard Monitoring and Control System (SMCS).

To achieve cost savings without degrading performance, the ASMP concept incorporates the use of a selected group of common machinery modules across several ship classes, flexible power-sharing generation and distribution architectures, specification of standard hardware components, and maximum use of common software and control strategies.

The fundamental assumptions of the ASMP approach are

1. The correct choice of machinery system architecture can produce significant changes in the ship construction process, removing machinery systems installation from the critical path, and reducing ship constmction time and cost.
2. A small family of machinery modules can be developed from which a variety of affordable systems can be configured to serve many classes of ships. The resulting systems meet all performance goals. Design, acquisition, and life cycle costs for a limited set of modules composed of standard components and designed with standard interfaces for multiple ship configurations are less than the corresponding costs for multiple unique machinery systems.
3. Electricity will be the energy medium in naval ships of the future.
4. The SMCS will be the means for transmitting and distributing information within the ship. The SMCS will also provide standards for monitoring and control systems hardware (4).

The ASMP architecture is comprised of basic power system functions and their respective interface characteristics. A power system function is described as a sub-system entity whose purpose and interfaces can be well defined. For the IPS, the basic power system functions are:

. Power generation of electrical power for shipwide use,
. Power distribution throughout the ship,
. Power loads for conversion of electrical power into usable forms of energy for propulsion, auxiliary systems, lighting, etc.,
. Energy storage centers which alternately act as a power load or power source, according to system requirements, and
. Power system control of the IPS.

Proper definition of these functions, specification of interface standards, and identification of prospective applications are the keys to producing a family of machinery module designs from which a variety of affordable IPS configurations can be developed (Figure 4). This being

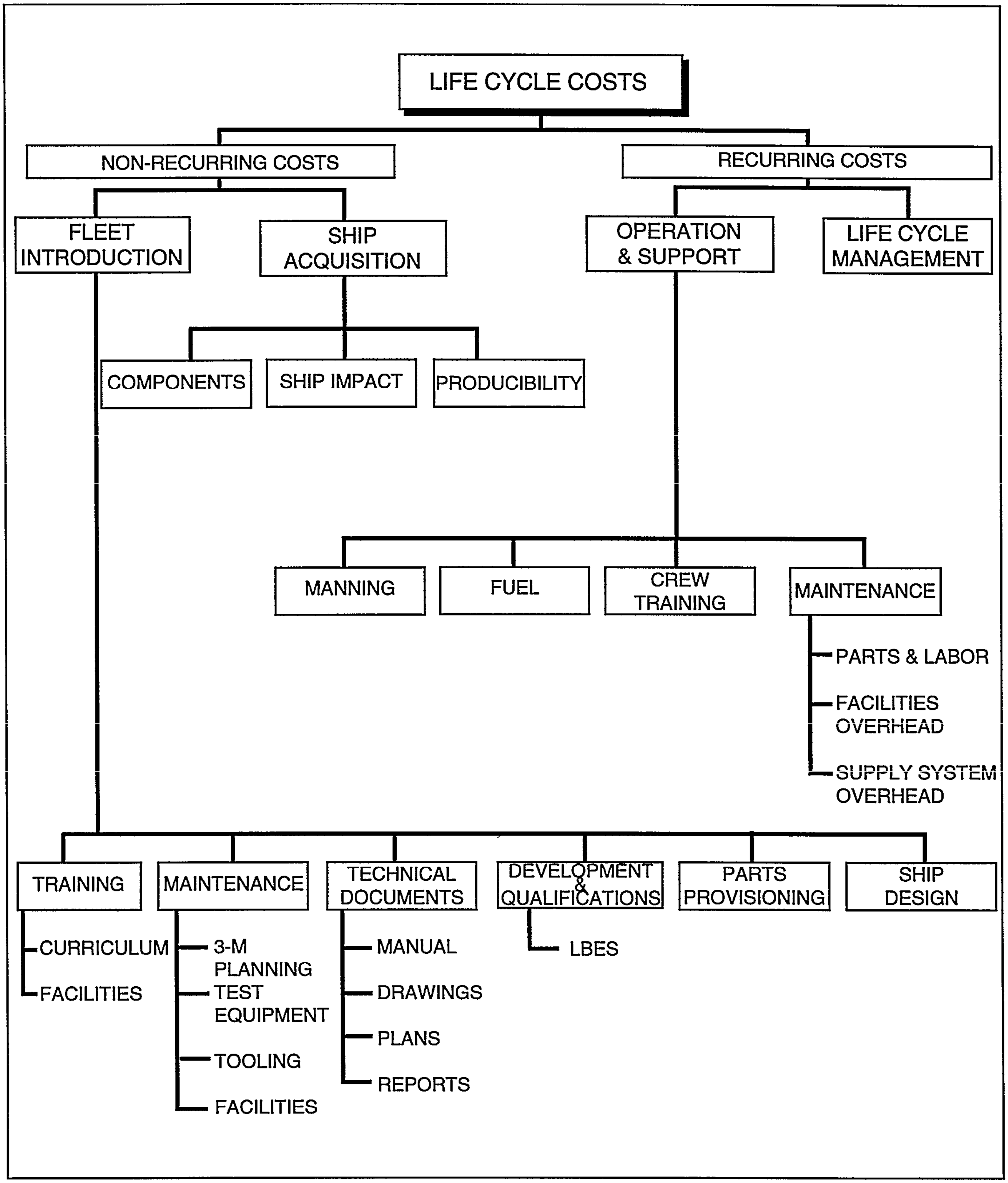


Figure 3. The ASMP Life Cycle Cost Model

done, ship machinery system design can be translated into a selection of the most economical combination of modules which satisfy machinery system performance requirements. A ship *configuration is* defined as the set of machinery modules (tailored as necessary) that meet specific ship performance requirements (Figure 5).

Thus, the design of a ship machinery system is essentially reduced to choosing the appropriate numbers and combinations of modules which meet ship requirements, using module characterization sheets to integrate these modules into the ship design. These characterization sheets provide Computer Aided Design (CAD) 3-D solid models and all other information required to incorporate these modules fully into the computer-aided ship design process (4) (Figure 6).

Electrical Systems

The Zonal Electrical Distribution System (ZEDS) represents a significant change in architecture from the conventional (radial) electrical distribution systems currently installed in naval ships. In conventional systems, electrical power is distributed by dedicated cables directly to user loads throughout the ship from a few centralized locations in the ship, namely the ship service switchboards and load centers. The result is thousands of cables running through all areas of the ship, crossing watertight boundaries and requiring significant portions of the ship for installation and protection. Phasing out of steam systems and proliferation of shipboard electrical and electronic equipment have contributed to an ever-increasing electrification of naval ships. At this point, the capabilities of radial systems have been pushed to the limit the electrical distribution system has become a significant factor in ship design and construction costs.

The ZEDS employs port and starboard longitudinal electrical busses to deliver power through the length of the ship. In each electrical zone, load centers tap electric power off the port and starboard busses, while distribution cables *located only in that zone* distribute power to user equipments in the zone. The principal components of the ZEDS are the port and starboard power busses, zonal load centers and associated switchgear (Figure 7). DC ZEDS assumes the availability of SMCS to provide monitoring and control services (5).

The ZEDS enhances ship producibility and affordability by reducing the amount of electrical cable required to be installed to support the ship's electrical distribution requirements, reducing the number of watertight bulkhead penetrations, and through the use of a solid sectional transmission bus enclosed in a protective duct as a planned replacement for conventional transmission cables (Figure 8). In addition, ZEDS allows the option of electrically connecting and powering all equipment in a given ship construction zone *before* it is joined to the rest of the ship, facilitating equipment test and checkout in a more accessible manner.

Auxiliary Systems

As a result of a strategic planning session held in November 1992, ATC is addressing the modularity of auxiliary machinery systems in two ways (6). From the large number of possible auxiliary machinery options considered, a Reverse Osmosis Desalinator Module (RODM) and a Zonal/Nlodular Heating, Ventilation and Air Conditioning (HVAC) system architecture were selected as the most promising candidates for development.

There are different reasons for the selection of these two tasks. Both are useful, fleetwide, and cost-reducing, yet their respective strengths and weaknesses are not the same, as shown in the tables below:

RODM STRENGTHS	ZONAL HVAC WEAKNESS
Backfit potential to fleet	**Requires ship architectural changes**
Low technical risk	**Difficult (new** thinking, research)
Attention getter	Obscure, esoteric
Good early building block	Long lead time (for results)

Table 1. Near-Term Benefits of the RODM

From the opposite view:

ZONAL HVAC STRENGTHS	RODM WEAKNESS

Table 2. Long-Term Benefits of Zonal HVAC

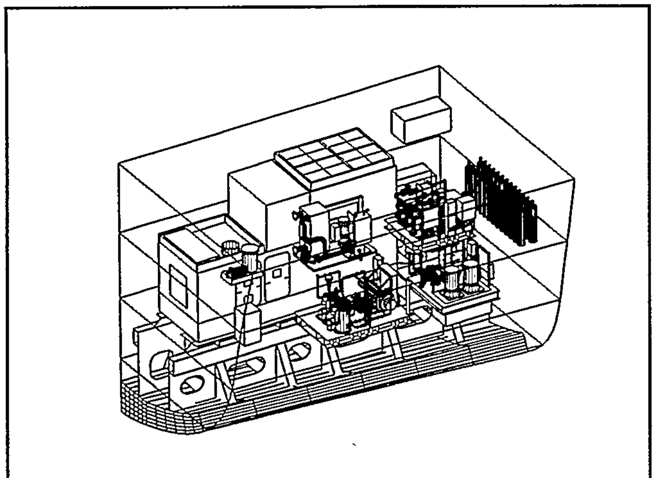
The reason for the selection of two candidates with such divergent attributes is that by exploiting the *benefits* of each, the auxiliaries team would use dramatically different cases to demonstrate the ATC approach to reducing ship cost. In one case, the team has taken the proven technol-

Power Generation Modules		Status
PGM 1	22 MW (29 KHP) ICR Generator Set	Under development
PGM 2	3.75 MW Diesel Generator Set	Concept design
PGM 3	3 MW Gas Turbine Generator Set	Existing
Propulsion Motor Modules		
PMM 1	20-25 KHP Single Rotation Motor	Under development
PMM 2	40-50 KHP Single Rotation Motor	Under development
PMM 3	50 KHP Contra Rotation Motor (Tandem 25 KHP Motors)	Concept design
PMM 4	Auxiliary Propulsion Motor	Existing
Electric Power Transmission/ Distribution/ Conversion Modules		
PDM 1	Propulsion Electrical Transmission System	Under development
PDM 2	**Zonal** DC Ship Service Distribution System	Under development
PDM 3	Zonal AC Ship Service Distribution System	Existing
PDM 4	Pulse Power Electrical Transmission System	Under development
PCM 1	Ship Service Power Conversion Module	Under development
Control Modules		
PCON 1	Supervisory Control Module	Under development

Figure 4. The Family of ASMP Modules

Ship	Power Gen	Prop. Motor	Elec Trans	Distribution	Control
SC-21	(2) PGM 1 (1) PGM 3	(2) PMM 1 (1) PMM 4	(1) PDM 1 (1) PDM 2 (1) PDM 4?	(7) PDM 3 (14) PCM 1	(1) PCON 1
Amphib	(2) PGM 1 (2) PGM 2	(2) PMM 1	(1) PDM 1 (1) PDM 2 (1) PDM 4?	(7) PDM 3 (14) PCM 1	(1) PCON 1
Dry Cargo	(1) PGM 1 (3) PGM 2	(2) PMM 1	(1) PDM 1 (1) PDM 2	(7) PDM 3 (14) PCM 1	(1) PCON 1
Repair	(1) PGM 1 (4) PGM 2	(1) PMM 1	(1) PDM 1 (1) PDM 2	(7) PDM 3 (14) PCM 1	(1) PCON 1
Sealift	(3) PGM 1 (1) PGM 2	(2) PMM 2	(1) PDM 1 (1) PDM 2	(7) PDM 3 (14) PCM 1	(1) PCON 1

Figure 5. ASMP Modules on Target Ships



Module Summary Characteristics

DESCRIPTION: PGM —1 Generation Module with ICR Gas Turbine Engine — driven Generator, and propulsion support submodules and systems.

SWBS Group: VARIOUS		SUPPORT RQMTS:	
		FW:	NONE
RATING: 22 MW @ 750 VDC		LO:	NONE
		SW:	7200 1/MIN
		Air:	TBD
DIMENSIONS:		HVAC:	TBD
Length:	12.80 m	Electrical:	TBD
Width:	9.25 m		
Height:	10.00 m		
WEIGHT: 204,052 Kg. (Est.)		UNIT COST:	

Figure 6. ASMP Power Generation Module PGM-1

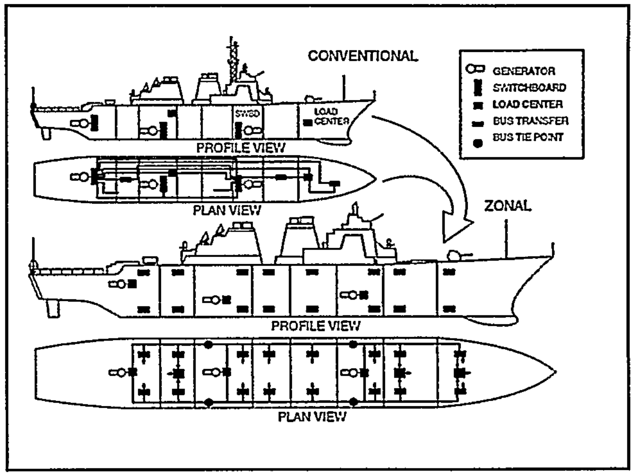


Figure 7. The Zonal Electrical Distribution System

ogy of the Navy's new Reverse Osmosis Desalinator and integrated five individual pieces into a stand-alone module with fleetwide applicability. This modularization provides the ATC team with a usable, near-term product that allows the team to demonstrate and improve certain aspects of the modular process using a relatively simple system. At the same time, however, the ATC marine engineers have taken on the challenge of developing a Zonal/Modular HVAC architecture. This concept features strict vertical subdivision of watertight ventilation zones which permit the use of modular HVAC and chilled water equipment. This is a decidedly more complex effort, but one which promises to have a significant impact on the way ships are designed in the future.

In addition to the RODM and Zonal/Modular HVAC initiatives, the ATC team is also investigating modular, common-family equipment for steering gear systems and an alternative firemain concept known as the single main/ zonal firemain architecture system. The first three efforts are discussed in greater detail below; the single main/zonal firemain architecture has been previously reported upon by the ATC team (7).

Reverse Osmosis Module Development

The Navy's newly developed and qualified 12,000 gallon per day reverse osmosis (RO) plant consists of four major pieces — membrane, pump and filter skids, and a control/gauge panel — which require the usual foundations and interconnections when installed aboard ship. The team's original intent was to mount these items in a well-considered arrangement on a single base. Fabricated and interconnected in the shop, this module could be landed in the ship as one unit, making the necessary seawater, freshwater, and electrical connections onboard.

Though still the basic approach to RODM development, discussions with the NAVSEA technical codes responsible for shipboard distillation (SEA 03X23 and SEA 03Y32) have indicated that the value of the RODM would be enhanced by the addition of several items. Since all ships do not strain seawater service to the same degree, a strainer of the required gauge for this RO plant will be added. The Navy's new electrolytic disinfectant generator (chlorinator) will be included in the module, since this is a logical part of a potable water plant. Because single-pass RO water is not pure enough for electronic cooling, gas turbine water wash or boiler make-up feed, the team is considering the addition of a small, second-pass unit for these special needs. Shock and vibration mounting options are also being reviewed.

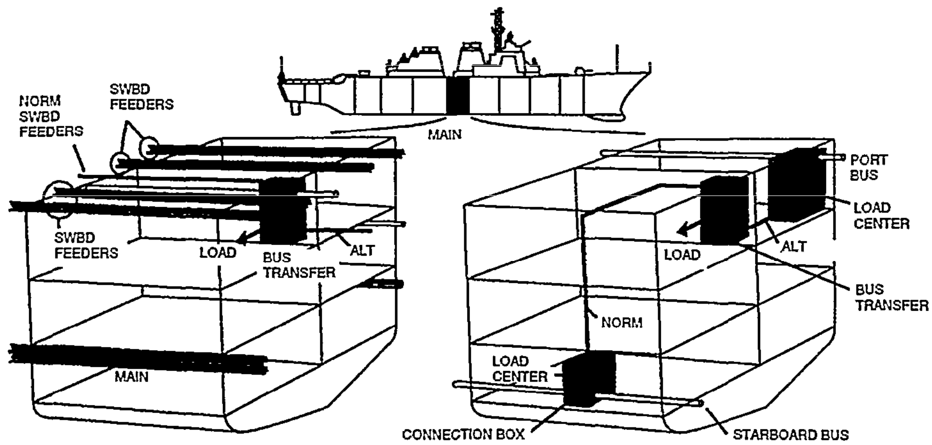


Figure 8. ZEDS Enhances Ship Producibility

The status of the RODM effort at the end of FY 93 includes development of an operability and maintainability test plan, and the completion of conceptual (Level I) arrangement drawings. The intent is to begin prototype module fabrication in late FY 94 using the Navy's prototype RO plant that recently completed shock and vibration testing, as well as the prototype chlorinator unit. An early conceptual drawing of the RODM is shown in Figure 9.

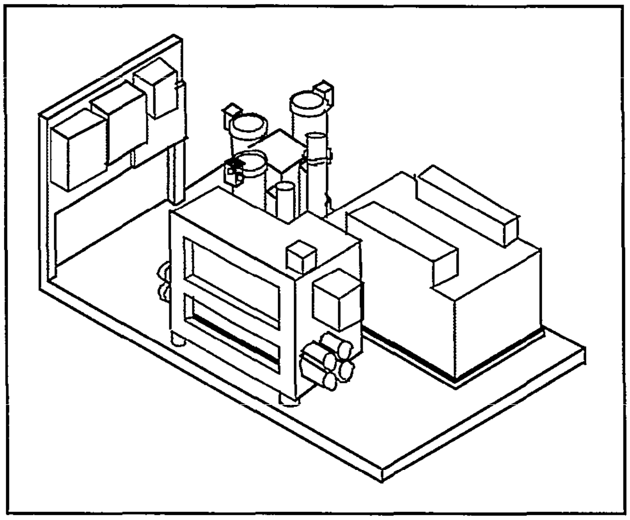


Figure 9. The Reverse Osmosis Desalinator Module

Zonal/Modular HVAC System Architecture

The primary performance attribute of the zonal HVAC system is to improve ship survivability by enhancing zone autonomy through strict vertical arrangement of the HVAC system on the ship's centerline. Accordingly, the ship is subdivided into watertight ventilation zones with separate, self-contained ventilation systems. The transverse bulkheads extending into the superstructure are smoke and fume-tight. Such a zonal architecture offers significant survivability advantages, as well as preventing the spread of smoke.

While the survivability aspects of a zonal HVAC architecture are quite attractive, the real incentive behind this study is the widely held belief that the current method of designing and building HVAC fan rooms and distribution systems is inefficient and expensive, and that the use of standard size modules to serve the needs of a simpler, more survivable zone is the most promising HVAC affordability option. To exploit economies of volume, ATC intends to develop common HVAC modules for fleetwide application in order to reduce HVAC design, construction, operating, and infrastructure costs overall (Figure 10). In addition to the HVAC system, ATC is examining various other distributive system architectures to dovetail with generic build strategies and other ship producibility efforts.

Because there are usually significant variations in

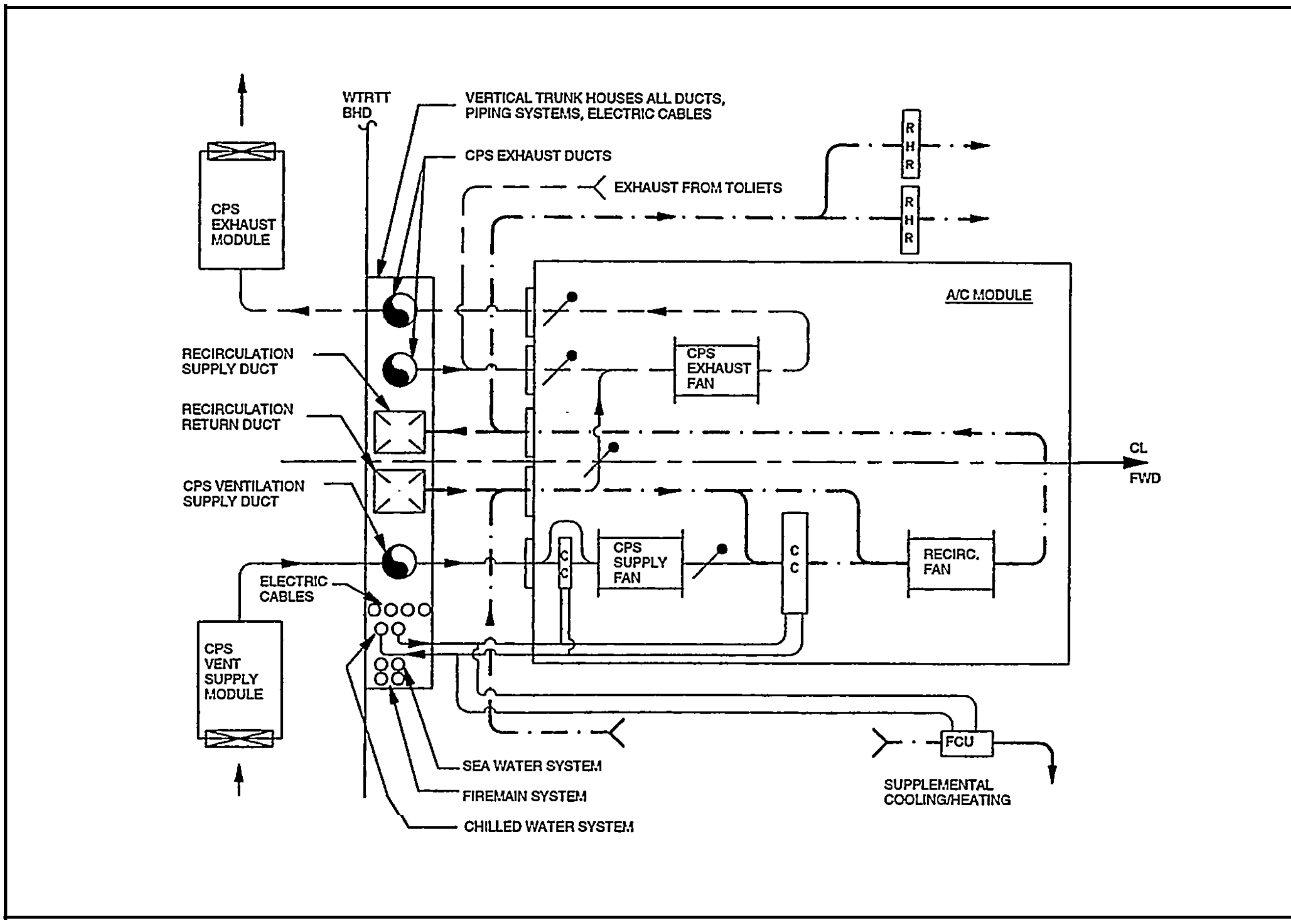


Figure 10. Functional Arrangement for HVAC Zonal/Modular Concept

HVAC requirements among the zones in any ship, it is difilcult to establish a “best fit” size for identical modules that can be used in multiples to meet the required load, particularly if it is intended to be used for an existing ship design. The step function aspect of module sizing can result in some zones which are over or under supplied, while other zones are right on the mark. Solving this problem is a matter of developing the connect common denominator module sizes, *and* designing anew ship such that the zones themselves are sized to take advantage of modular equipment. In addition, it is important to note that changes to existing HVAC requirements and design criteria may be required should development of Zonal/Modular HVAC architecture prove advantageous in naval ships.

The issue of HVAC design practices and requirements has been one focus of ATC team efforts in FY 93. Through consultation with the NAVSEA HVAC technical code (SEA 03V21), design criteria considered sacrosanct, those that could be changed to facilitate development of zonal architecture, and those considered relatively unimportant or unnecessary in a zonal configuration have been identified. The ATC team is currently working to develop workable updates to design criteria that would be violated by a Zonal/Modular HVAC system. A sampling of these issues is:

. Vital space independent of twin separate recirculation systems,
. Collective Protection System (CPS) design philosophy,
. Damage control classification (W,X,Y,Z) for zonal architecture,
. Airlocks between zones,
. Weather openings for zones that do not service superstructure, and
. Combat system (or AEGIS) cooling system failure analysis.

Development of zonal HVAC distributive systems, modular fan rooms, weather terminals, and chilled water plants will proceed in FY 94 as their respective design criteria issues are resolved.

Steering Gear

In the ATC team, the initial impression was that commonality of steering gear generally existed throughout the fleet. Closer inspection revealed that although the predominant number of systems were of the Rapson slide actuator type, size consistency between ship classes did not exist. Furthermore, it has been determined that there are technically acceptable alternative concepts which offer a more cost effective configuration. These include double-acting, single-ended cylinders and hydraulic power units employing vane-type double pumps. This concept is particularly appropriate for amphibious assault and auxiliary ships.

With respect to combatant ships, it appears that the Rapson slide and variable swash plate-type hydraulic pumps in a standard design with a family of sizes would be the most appropriate steering gear system. This equipment would also facilitate the incorporation of rudder roll stabilization in future ships.

With the knowledge this limited study provided, the ATC team intends to consider developing families of steering gear modules that have fleetwide application.

Standard Monitoring and Control System

Like the machinery systems themselves, machinery plant monitoring and control systems have traditionally been custom-designed for each class of ship. Little effort has been made to use common hardware or sofhvare within a given ship type or across ship classes. In turn, in-service engineering and logistics support capability have been developed and maintained for each of these unique control systems. Consequently, developing and supporting Navy machineV monitoring and control systems has proven to be very expensive.

The SMCS is a program element of ASMP which can significantly reduce the costs of developing and supporting monitoring and control systems for shipboard machinery systems. The use of only four unique enclosures can meet all hardware requirements for an integrated monitoring and control system (Figure 11). SMCS also provides an improved information architecture which ensures accurate and reliable transfer of information between modules and control stations in a machinery system. SMCS differs from current proprietary shipboard control systems by incorporating open standards and an open architecture. By avoiding proprietary systems, SMCS can enable multiple vendors to supply compatible hardware and software without contractual complications. SMCS also supports a software repository from which software modules can be selected to complete a control system package. In this manner, the amount of configuration specfic software (and attendant cost) is kept to a minimum.

The SMCS consists of core hardware and software for developing machinery monitoring and control systems for

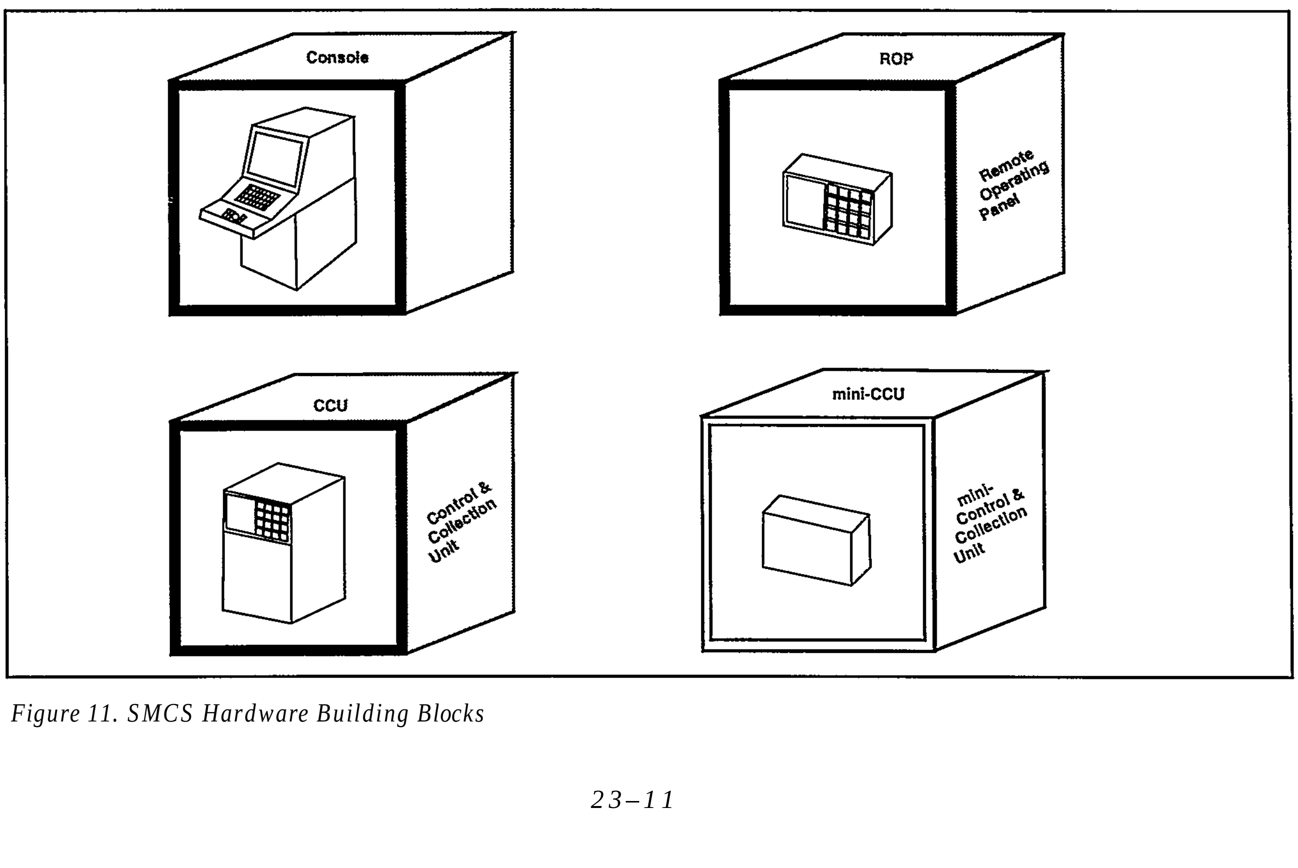


Figure 11. SMCS Hardware Building Blocks

backfit, forward fit, and new construction ships. SMCS hardware consists of standardized consoles as well as Control and Collection Units (CCUS) and Mini-Control and Collection Units (mini-CCUs). The consoles and CCUS are interconnected by a fault tolerant data communication standard, such as SAFENET II. Mini-CCUs communicate with CCUS via a local data communications standard such as MIL-STD-1552. The CCUS and mini-CCUS interface directly with machinery plant equipment comprising the propulsion, electrical, auxiliary and damage control systems (Figure 12).

The SMCS core software repository provides a collection of reusable modules from which a variety of monitoring and control systems can be easily developed. SMCS is intended to support the following systems:

- Mechanical drive propulsion plants (Gas turbine or diesel),
- Integrated Power Systems,
- Zonal Electrical Distribution Systems (Zonal AC and Zonal DC),
- Integrated Survivability Management Systems (ISMS),
- Zonal auxiliary systems,
- Condition Based Maintenance, and
- Onboard training.

Combat Systems

In the area of Combat Systems modules, ATC is building on earlier progress in modularity and standardization. VLS missile modules and AEGIS electronic modules have proven to save time and cost of installation; testing of completed modules can be accomplished offship and installation can be deferred until the zone in which the equipment is to be installed is ready to accept it. In addition, upgrades and modifications (e.g., missile load out mix) are easily accomplished.

One of the key objectives of ATC is to shift assembly and test to shop and on-block locations. For combat systems equipment this is particularly applicable to the assembly of guns. Currently, guns are built into the ship during initial construction. This includes machining the roller path in the deck and in situ assembly of gun components (e.g., train and elevation assemblies, ammunition hoists, ready service room equipment etc). Significant cost savings in this process are possible if the gun can be

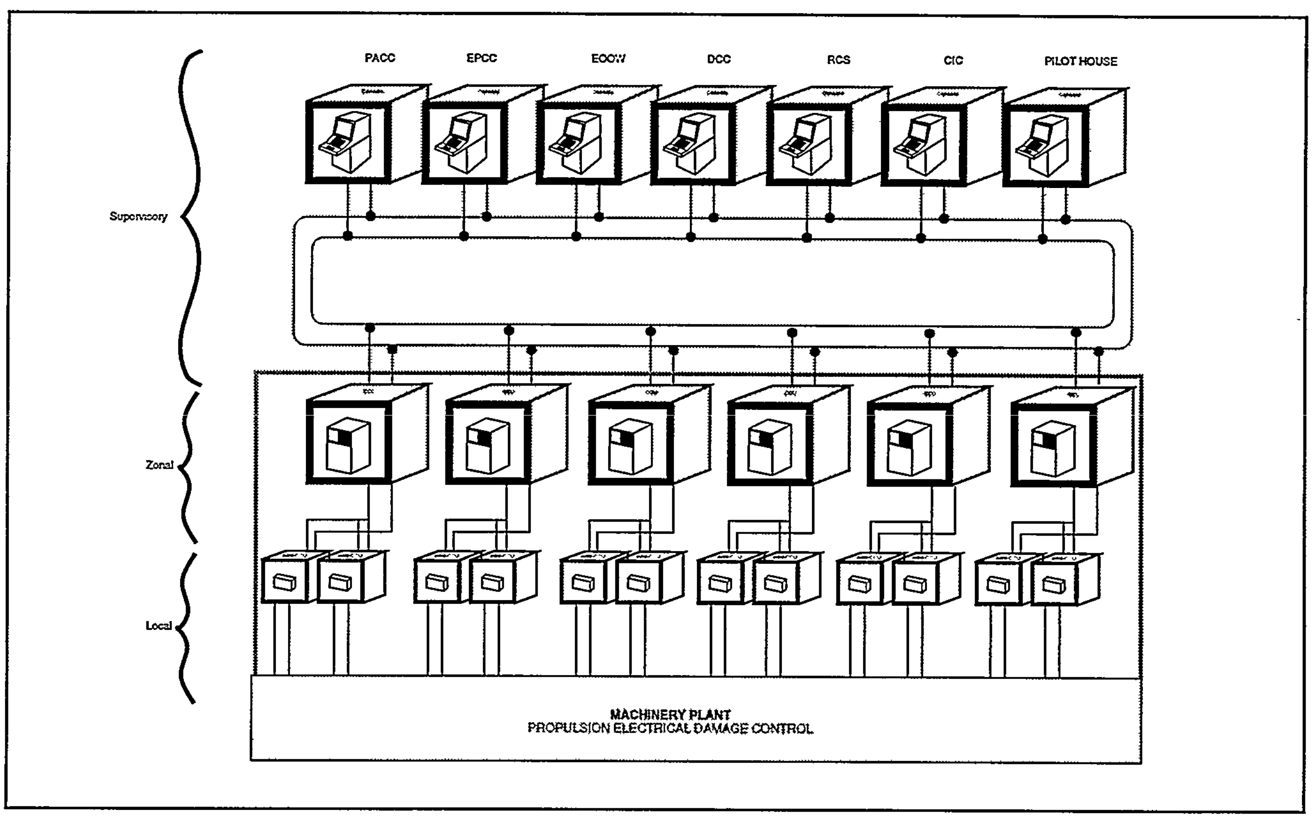


Figure 12. The Standard Monitoring and Control System

packaged as a module. This has been demonstrated in foreign built ships such as the Blohm and Voss MEKO modular frigates. Nearly 60 of these frigates have been built over the last ten years; several of these contain a 127mm (5 inch) modular gun.

To capitalize on this experience, ATC is proposing a foreign comparative test program for a modular 5"/54 caliber gun system (MGS), based upon the MEKO system. The MGS will consist of the 5"/54 caliber gun assembled in an installation module. The MK 45 5"/54 caliber gun is standard in the U.S. Navy and will remain so beyond this decade. AA-size module installations, which provide the gun mount structural support, are fully outfitted with gun ancillary equipment and provide all gun/ship system interconnections. The modular concept allows gun system pre-outfitting and intra-system testing prior to ship installation in a protected environment. This, in turn, reduces shipboard outfitting and checkout time, promotes installation standardization, and facilitates in-service gun system replacement time. This approach also eliminates the time consuming process of machining the gun mount and ship interface onboard ship, and simplifies the on-board alignment of the pre-machined loader mechanism. The MGS provides near term results for the ATC program in that it has widespread application throughout the fleet. The MGS is shown in Figure 13.

In addition to modular ordnance systems, ATC will review current and future combat system functional elements with the approach that increased modularization and interface standardization will facilitate improvements in offship testing and ship installation, as well as ease of upgrade and contracting control. This effort will determine the functional groupings of respective equipment. Some of the criteria to be used in this determination include:

- Mission association and/or relevance,
- Manufacturer commonality,
- Production and/or integration testing,
- Maintenance access,
- Equipment size and/or weight,
- Service needs,
- Structural and/or subdivision boundaries,
- Secondary removal and/or replacement,
- Ship access and/or zone location,
- Cabling termination, and
- Installation procedures.

To assist in development of the above criteria, dockside and shipboard testing will be examined in detail. Using ATC modularity and interface standards, existing procedures for Total Ship Test Program Stages 2, 3, and 4 might be greatly simplified through offship testing.

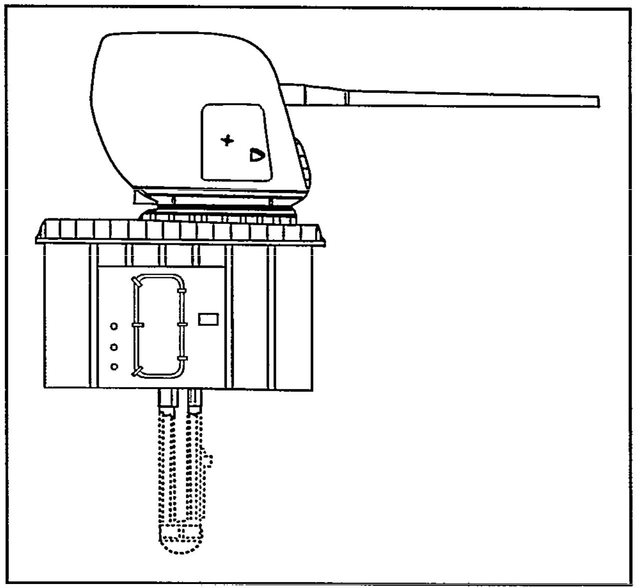


Figure 13. The 5"/54 caliber Modular Gun System

For example:

Stage 2 - Installation, Inspection and Tests. These tests demonstrate that integrity, strength, and continuity are applied to foundations, cabling, sonar domes, piping, ventilation, air conditioning, switchboard, interface connections, etc. in accordance with module/module station installation requirements.

Stage 3 - Equipment/Equipment Group Assembly Tests. These tests demonstrate that individual or groups of equipments perform within specified tolerances. Included are safety checks conducted prior to equipment operation, as well as initial light-off tests.

Stage 4 - Intersystem/Integrated Combat System Tests. These tests demonstrate that two or more independent but interfacing combat system elements perform within specified operating and alignment tolerances. This includes the exchange of intersystem signals, commands, functions, and associated software interfaces.

Installation and Integration

The correct choice of systems architecture can reduce ship construction costs by enabling improvements in construction efficiency. The modern concept of shipbuilding is to construct and outfit large ship assemblies (zones) which are then welded together to form the ship. System architectures can maximize the benefits of such a construction process by minimizing and simplifying the system interfaces across ship assembly zone boundaries. Unfortunately, current ship designs do not fully support

this process. An example is that propulsion shafts require careful alignment through multiple zones, while conventional electrical distribution and other distributive auxiliary systems require hundreds of pipes, ducts, and power cables to cross ship construction boundaries.

The ATC/ASMP approach is specifically intended to facilitate the zonal ship construction process. The IPS removes the requirement for long shaft lines. Zonal electrical distribution reduces the number of cables crossing construction boundaries. The SMCS reduces the total amount of machinery system control wiring. The use of machinery and combat system modules allows maximum assembly, outfit and pre-testing concurrent with the earliest stages of the ship construction process.

Fully outfitted and pre-tested, these modules are transported to the construction site for integration into ship assemblies. When construction and outfitting of a ship assembly zone is completed, the equipment and systems within the zone can be tested as an independent section of the ship. (Module tests which duplicate factory tests are not required.) When zonal tests are completed, the assemblies are joined to form the ship. The necessary final ship systems tests are then accomplished. In general, tests accomplished in the earliest possible phase of the ship construction process enable monitoring, troubleshooting and repairs in the least costly manner.

Successful integration of these modular assemblies will require strict discipline by the shipyard to check, reassemble as required, align and connect support services if problems are to be avoided. Receipt and inspection criteria includes such elements as: visual inspection, standard equipment lists (for module components), packing, handling, storage, transportation, test, Quality Assurance (QA) and Integrated Logistics Support (ILS) documentation. Experience by shipyards who have been utilizing modularity for nearly twenty years indicates that such an approach facilitates control of vendor equipment. In fact, there was a marked improvement in quality and a minimum adverse impact when these responsibilities were established. This eliminated confusion and overlap of efforts.

Even with an increase in the number of modules provided to the shipyard, the yard will have to assemble several of these together into a larger unit. At this point, assembly criteria will have to be established which will include structural methods, service interface placement, service interface connection assembly, construction tolerances, weight and dimensions limits, materials, and workmanship. For example, for many modules and subassemblies, alignment will be critical. Such issues as environmental considerations, perpendicular and/or parallel structure criteria, bolt hole alignment and foundation flatness requirements must be addressed. To assist in easy alignment of foundations, it is expected that special tools and jigs and/or drill fixtures will be used extensively (Figure 14).

Some of the shipyard functions associated with module integration and installation will include preinstallation interface checkouts. This will require criteria for interface checkout of tools and instruments, standard connectors and parts, working access and clearances, piping, cable, duct sizes, and quality. Such interfaces will also be controlled onboard ship, either as part of on-block outfitting or final construction. Successful implementation of this process will depend on the ability to validate module fluid, electrical, HVAC, and control system interface requirements (Figure 15).

Handling criteria may have to be developed for some types of modules, as there maybe some unique requirements associated with the equipment in these modules. Handling criteria would include lift weight data and safety factors, access and egress planning, acceptable deflection and stress limits, and overall safety measures. For heavier modules, such details as lifting methods, chainfalls, sling designs, braces and strongbacks maybe designated.

The need for dialogue with shipyards during the development of the ATC/ASMP approach to installation and integration cannot be overemphasized. If the production process is to be streamlined, the use of common modules can play a key role.

Costing

Material, whether contractor-furnished or Govemment-fumished, represents over 60 percent of the cost of any naval ship. Using standardization and large volume procurement, the cost of this material can be reduced by 30 percent. In light of previous experience with the DD-963 class destroyers, this estimate is very realistic. Such a reduction would result in an 1 S percent reduction in overall ship unit cost.

Increased productivity due to use of modular subassemblies has been shown to reduce overall ship construction costs by 10 percent. In addition, by shortening the detail design and construction cycle from 49 months to 36 months, overhead (management and facilities) costs of ship construction could be lowered by 5 percent. Thus, full implementation of the ATC policy could yield a reduction in ship acquisition cost of 33 percent, approaching the 40 percent actually achieved by the Japanese (2).

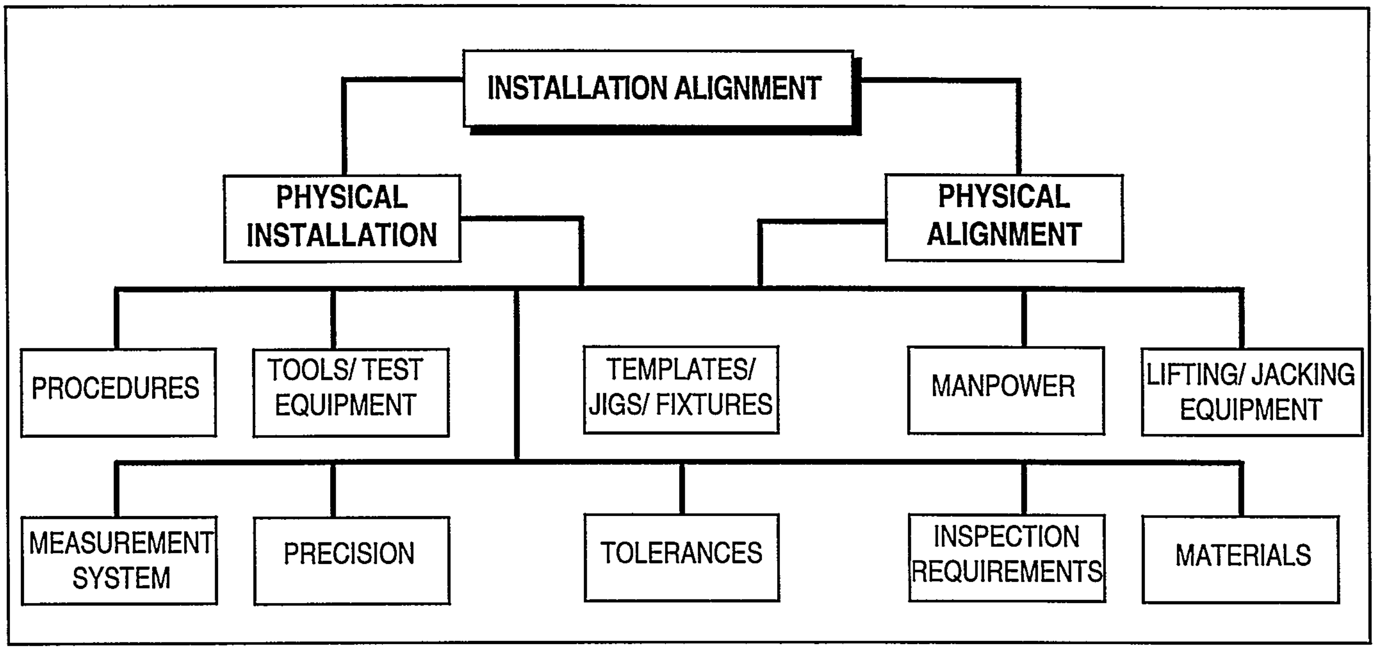


Figure 14. Installation Alignment Criteria

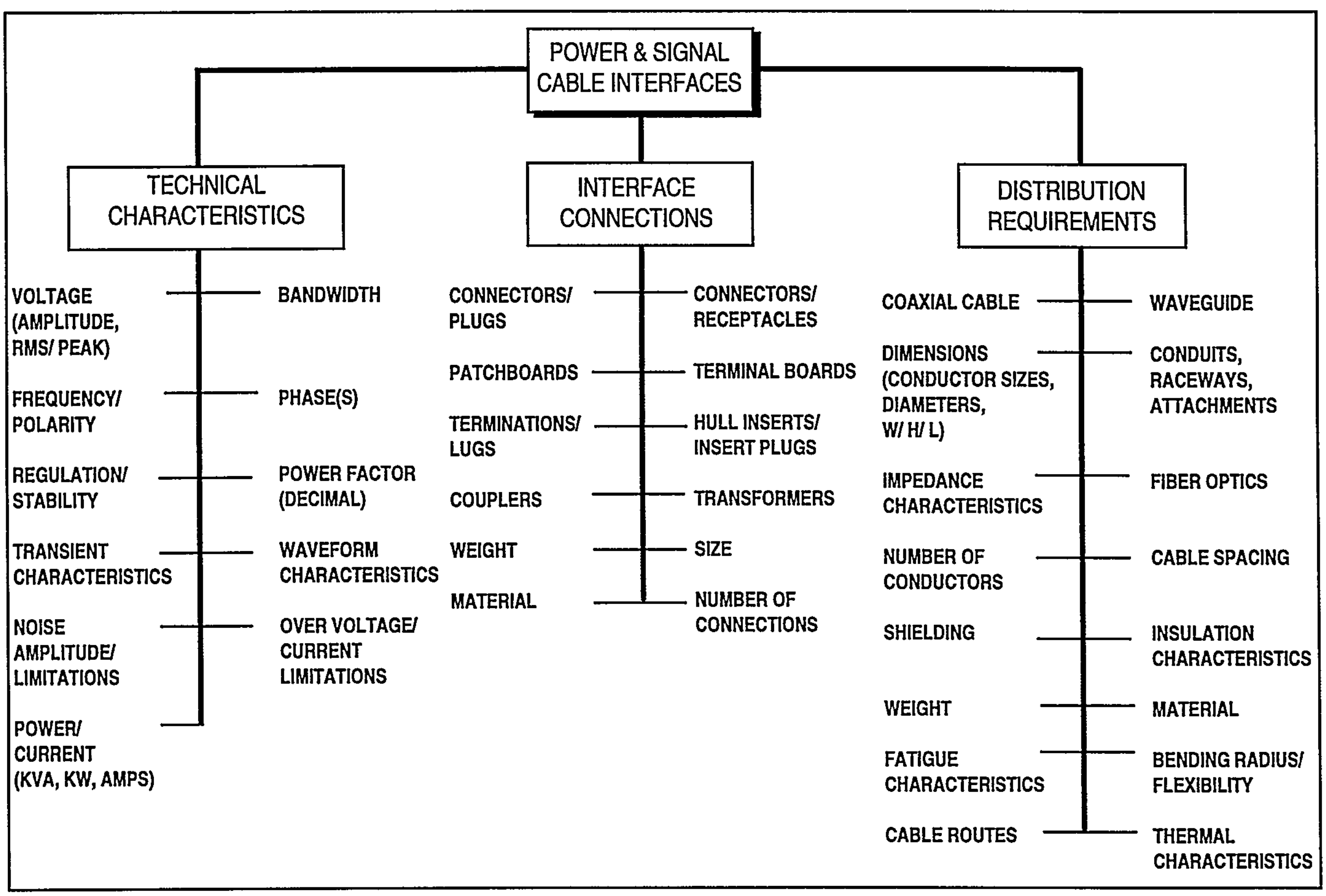


Figure 15. Power and Signal Interface Criteria

To further reduce production costs, military quality control oversight should be aligned to the maximum extent possible with comparable industrial standards, such as ISO-9000. Special fabrication processes should be used only where absolutely necessruy. Ideally, cost accounting and program management should allow use of the same methods and facilities for both commercial and military manufacturing projects. In this context, any factory test conducted to verify module integrity/operability should eliminate the need for the same testing at the ship construction site, prior to ship integration.

The Navy's acquisition strategy for a given type of equipment or class of ships will determine how common modules will be procured. They may be obtained from a government item manager as Government Furnished Equipment (GFE) or constructed by a specialized integrator (including the building shipyard). As long as module specifications are followed, the most cost effective acquisition method should be chosen.

Ship design will be impacted by the ATC process in that it can start to proceed with a set of known building blocks which have been thoroughly reviewed by design, procurement, construction, life cycle management, and operational personnel. Such approaches to module development have been adopted by Martin Marietta with impressive reductions in costs. A design change which costs $100 to make in the product design phase would cost $100,000 for the comparable system modification to be accomplished in the field. With the ATC approach, these product design changes can be accomplished more rapidly. It is estimated that the overall ship design, procurement, and production cycle could be reduced from 111 months to 72 months - a reduction of 39 percent (Figure 16). Even allowing for multiple reviews during combined preliminary/contract design stages (including shipyard and module manufacturer representatives), the schedule still allows two years for the design of a Navy ship.

Future direction

The combined ATC/ASMP project is oriented towards providing commonality options to ongoing and future ship acquisition programs. These options must be offered early enough in the design and acquisition cycle to impact procurement decisions. In addition, there should be enough equipment production volume to realize measurable cost savings from early commonality-based products. This philosophy has led to an emphasis on providing commonality options for the LX amphibious assault ship and the DDG-51 guided missile destroyer, Flight DA. Upcoming years will see the continued development of commonality products and procedures selected for utilization by these programs, and the expansion into providing similar options for future ship designs. The general plan is to expand from the early ATC base in HM&E and weapons systems equipment into the broader field of combat systems and

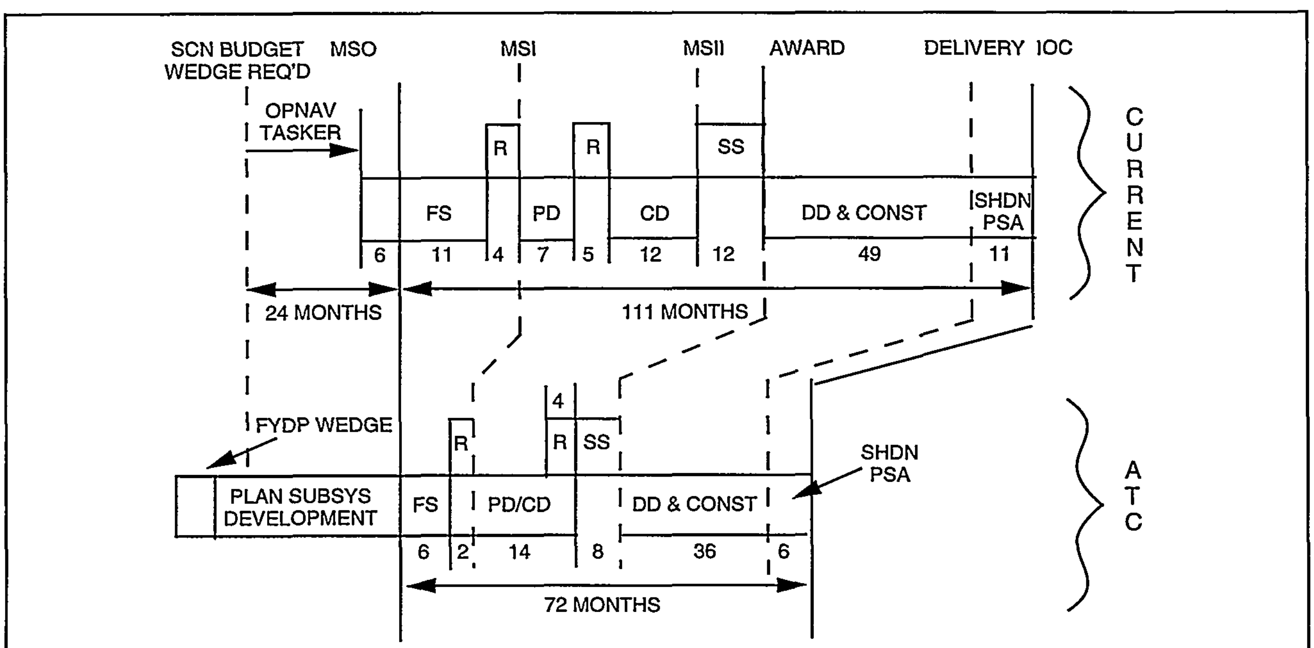


Figure 16. Comparison of Current versus ATC Design and Construction Milestones

communications. The goal is to map the feasibility and format of commonality for the *whole ship* and for *every ship,* over the course of a ten year project life. Providing full commonality-based options for ships contracted after the year 2000 and revised, affordable processes for NAVSEA to implement as the mainstream process for conducting naval ship design, acquisition, and in-service support is the ultimate goal of ATC. The extent and success of this implementation will be measured by the degree of architectural impact on such post-2000 ships as SC-21 (future surface combatant) and LVX (Mure flight deck amphibious assault ship).

SUMMARY

The ATC project is in the first developmental year of a multi-year task. It is estimated that seven to ten years of steady effort and reliable funding are required to achieve a commonality-based design infrastructure that can dramatically benefit the affordability of the acquisition process and eventually the in-service support process. These benefits can be phased into each subsequent new ship design as various prototype modules, design and cost tools, generic build strategies, and databases are developed and accepted for use by the Navy ship design and acquisition community.

This effort is consistent with recent recommendations of the Defense Science Board in the areas of Integrated Product and Process Development (IPPD) and dual-use manufacturing (8). The process improvements of the Navy and the commercial maritime industry can and must dovetail to restore balance of performance, quality, and affordability to the design, construction, and operation of America's ships.

REFERENCES

1. "Modularity, Standardization and Simplicity - Three Keys to a More Affordable Navy:' by RADM M. S. Firebaugh and CAPT Robert Percival, presented before the 1992 Ship Production Symposium in New Orleans, 2 September 1992.

2. "Naval Ship Affordability: Assessment of Increased HM&E Commonality Across Ship Types," NAVSEA Report 070-05R-TN-O04, May 1993.

3. "Improvements in Ship Affordability," by CDR Michael Bosworth and Jeffrey Hough, presented before the SNAME Centennial Meeting in New York, September 1993.

4. "Integrated Power Systems for Amphibious and Auxiliary Ships," by LT Norbert H. Doerry, USN, Advanced Surface Machinery Programs Office, Naval Sea Systems Command (NAVSEA 05Z), 23 June 1992.

5. "Zonal Electrical Distribution Systems: An Affordable Architecture for the Future," by Chester R. Petry and Jay W. Rumburg, <u>Naval Engineer's Journal</u>, May 1993.

6. "A Strategic Plan for the Affordability Through Commonality Project," prepared for CDR. Michael Bosworth (NAVSEA 05R3) by Decisions & Designs, Inc., December 1992.

7. "Development of a Zonal Architecture Fire Main System for Combatant Ships," by Mark E. Shiffler, <u>Naval Entineer's Journal</u>, May 1993.

8. <u>Engineering in the Manufacturing Process</u>, Defense Science Board Task Force Report issued by the Office of the Under Secretary of Defense for Acquisition, March 1993.

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Thermal Spray for Corrosion Control: A Competitive Edge for Commercial Shipbuilding

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ABSTRACT

Thermal spraying of steel with aluminum to protect it from corrosion is a technology that has been proven to work in the marine environment. The thermal spray coating system includes a paint sealer that is applied over the thermally sprayed aluminum; this extends the service life of the coating, and provides color to the end product. The thermal spray system protects steel both through the principle of isolation (as in painting) and galvanization (as in galvanizing) . With this dual protection mechanism, steel is protected from corrosion even when the coating is damaged.

The thermal sprayed aluminum coating system has proven to be the most cost effective corrosion protection system for the marine environment. However, unti 1 recently the initial cost of application has limited its use for general application. Today a new arc spray technology has reduced the application cost of thermal spraying aluminum to below that of painting. Commercial shipbuilders could use this technology to enhance their market position in the marine industry.

INTRODUCTION

It is time to put thermal spray aluminum technology to work. The technology has been proven to provide more than 20 years of maintenance-free service in the marine environment and can now be applied at a cheaper cost than painting. The technology was extensively analyzed by the Navy[1]s David Taylor Research Facility at Annapolis, Maryland. A series of fault and no-fault tests were conducted, using the Navy paint system as a standard. These tests, conducted over a five year period proved the thermal sprayed aluminum coating system provided corrosion protection better than painting, even when the coating was so severely damaged as to expose bare steel. These same tests also proved that flame wire and arc wire processes produce coatings that provide acceptable corrosion protection.

For more than fifteen years the Navy has been applying thermal spray aluminum coating to high corrosion areas aboard ships, and to dry dock facilities. Actual field applications, such as, weather decks, oil tanks, bilge tanks, ballast tanks, sanitary spaces, sewage holding tanks, fresh water tanks, fuel tanks, steam valves, etc. have provided testimonial success of the technology.

All the thermal spray processes produce coatings that will protect steel in the marine environment for long periods of time. The arc spray process is the only one currently available that allows the thermal spraying of aluminum to be performed cheaper than painting. Additionally, the results are of higher quality and provide the longest service life.

IMPLEMENTING THE THERMAL SPRAY PROCESS

A thermally sprayed aluminum coating, unlike paint, is resistant to abuse, and will therefore not be damaged by normal fabrication practices; this allows the coating to be applied during the construction process. The most cost effective production practice, with the highest quality of work, would be obtained by thermal spraying subassemblies and individual parts in the shop, where accessibility would be better, and automated processes could be utilized. Welding over the aluminum coating will not normally effect the steel's physical and chemistry properties, however, it does effect the welding characteristics; so welding over the thermal sprayed coating is not a good idea. The weld areas should be masked or the thermal sprayed coating can be removed with the same methods used to remove paint or galvani.zi.ng by grinding, sand blasting, or water blasting.

APPLICATION COST REDUCTION

The introduction of the arc spray process to corrosion protection applications has reduced the cost of thermal spraying, and has also facilitated a cost reductions in surface preparation and sealer application. The combination of these process improvements have made the thermally sprayed aluminum coating a viable cost alternative to paint coatings.

Surface Preparation

The high cost of surface preparation for the flame spray process is due to the fact that it requires a double blast operation. The first operation, performed with any blasting material, cleans the steel. The second blast operation establishes the required anchor tooth , and further cleans the material to a white metal finish. Aluminum oxide grit or chilled iron grit is normally specified for this second blast. Even with these precautions ultra clean practices are required to maintain surface cleanliness until it is coated.

Arc spray is much more forgiving to surface cleanliness requirements, and requires blasting standards similar to painting, with the exception that arc spraying requires blasting with an angular grit to achieve a anchor tooth pattern of 50um (2 roils) or more. The optimum surface preparation condition for both painting and

arc spraying is metal that has been cleaned to white or near white; this cleanliness requirement can be achieved with mineral slag grit material such as garnet, copper slag, and nickel slag in sieve sizes of 24-36. The cost of these grits in bulk quantities is about $.066/kg ($.03/lb), as compared to $.66/kg ($.30/lb) for the aluminum oxide grit which is required for the flame spray process (Table I).

	PAINT/ARC	FLAME
COPPER SLAG $.066/KG ($.03/LB) 73 KG/M² (15 LBS/FT²	4.83 (.45)	4.83(.45)
ALUMINUM OXIDE $.66/KG ($.30/LB) 29.28 KG/M² (6 LBS/FT²		19.39 (1.80)
LABOR	10.76 (1.00)	13.45 (1.25)
TOTAL US $	15.59 (1.45)	37.67 (3.50)

per square meter (square foot)

Table I: Typical surface preparation costs

The arc spray process provides a higher quality coating with the single surface preparation method than the flame spray process does on the dual blasting method. This is because the high energy of the electric arc causes the spray material to super heat and bond to the steel at strengths three to four times that of flame spray (Table II). The coating is also **more** ductile (softer) and will withstand more abuse.

ARC (wire)
316-421 KG/CM² (4.5K-6K LBS/IN²)
FLAME (wire)
105-246 KG/CM² (1.5K-3.5K LBS/IN²)
K=1000

Table II: (Typical) bond strengths for arc wire and flame wire processes

Sealer Application

Sealers are required for the thermal sprayed aluminum coating. The sealer enhances the performance of the coating by filling its pores, and isolating the aluminum from the environment. Without a sealer the life expectancy of a thermally sprayed aluminum coating would be decreased by a factor of three or more. A thin coat sealer performs better than a thick coating, making it more desirable to apply a thin coating system rather than a multiple layer thick coating system.

A thin sealer allows a considerable cost savings, and a reduction in <u>volatile organic compounds</u> (VOC) emitted to the atmosphere. The British, whom has more experience in thermal spraying ships, discourage a thick sealer system and specify a single coat wash primer system in their standard. The U.S.

Navy specifies a thin coating sealer system for high temperature steam valves; this application in itself verifies that the single coating practice satisfies the sealing requirements. A thick paint sealer can blister and create a pocket for moisture to gather. This stagnant water deteriorates the thermal spray coating under the blister, leaving the steel without protection at that paint. Blisters do not form on a thin sealer system to cause this problem.

For marine applications where color is not needed, a single coat sealer system is the preferred method. For example, a Mare Island Formula 150 primer thinned with an equal amount of solvent will provide the required protection. When a specific color is specified a thinned second coating material applied over the original sealer, and applied just thickly enough to provide color, is all that is required and recommended.

The Are Spray Process Improvements

The spray rate of the arc spray process has significantly reduced the labor required to apply the thermal sprayed coating. Spray rates for aluminum have changed from an average of 3.4 kg/hr (7 1/2 lbs/hr) to over 15.8 kg/hr (35 lbs/hr). This has been accomplished through inventions that allow the arc spraying of aluminum wire with diameters of up to 4 mm (5/32 inch). Other representative spray rates and coverages are shown in Table III. Deposit efficiency has also improved with the spraying of larger diameter wires; the efficiency is now more than 75%, which is equal to or better than the deposit efficiency of the flame spray process.

WIRE SIZE MM (IN)	AMPS	MELT RATE PER HOUR KG/HR	(LBS/HR)	COVERAGE PER HOUR 250um/FT² (10mil/FT²)
2.38 (3/32)	300	10	(22)	88
3.17 (1/8)	400	12.7	(28)	112
3.96 (5/32)	500	15.8	(35)	140

Table III: (Typical) arc wire spray rates

Improvements in arc spray equipment design and reliability have lowered costs of operations, and significantly increased labor efficiency, see table IV for process comparison. Training personnel to perform thermal spraying can be completed in just a couple days; this includes learning the skills to maintain the equipment. Operations are simple: the equipment turns on and off with one switch and spraying is started immediately without preheating of the substrate material.

	PAINTING	FLAME SPRAY	ARC SPRAY
ENERGY	X	.13	.01
SURF PREP	1.45	3.50	1.45
SEALER*	X	.70	.70
PRIMER*	1.35	X	X
COLOR#l*	1.35	1.35	1.35
COLOR #2*	1.35	X	X
METALSPRAY*	X	2.75	1.83
TOTAL US $/FT²	**5.50**	**8.43**	**5.34**

*INCLUDESLAEOR AND MATERIAL

Table **IV**: Process cost comparison

CONCLUSION:

Through the use of thermal spray, the United States shipbuilding industry could enhance their market position. Marine products could be guaranteed for more than twenty years against corrosion. Coating costs could be lower and environmental hazards could be reduced. Volatile organic compounds, a hazard in paints, could be reduced by more than ninety percent, or possibly eliminated. Because corrosion allowances would not be needed structural steel thicknesses could be reduced, increasing pay load and reducing fuel costs. Double hull technology would be enhanced by the long term protection of thermally sprayed coatings; which have been validated by both laboratory and field applications.

The high deposition arc spray technology has facilitated lowering the cost of thermal spray to below that of painting, while providing the highest quality coating. The process is forgiving to surface cleanliness requirements, allowing it to be used as a normal production practice with few special precautions. It is a process that can be operated manually or automated using conventional or robotic equipment. The process does not require special skills, and almost anyone of any background can be trained, to operate and maintain the equipment.

It is time to put the thermal sprayed aluminum technology to work in providing corrosion protection to our marine products and to provide a market edge for the United States shipbuilding industry. The coating will provide more than twenty years of corrosion protection for marine products, three to five times the life of a standard paint system. It can be applied on any size component in the field or in the shop, and the thermal sprayed aluminum coating system is now cheaper than painting and environmentally safer.

ACKNOWLEDGEMENTS

The high deposition arc spray process was developed with the assistance and valuable experience and knowledge input from employees of Puget Sound Naval Shipyard. Funding was provided by Naval Sea Systems Command and David Taylor Research Center. Legal services for Patent applications were provided by the Navy Patent Office.

REFERENCES

1. B.A. Shaw, A.G.S. Morton, "Final Report, Five Year Evaluation of Flame and Arc Sprayed Aluminum, Zinc, and 85/15 Zinc/Aluminum". Marine Corrosion Branch, David Taylor Research Center, Bethesda, Maryland, 20084.

2. BS5493:1977 Code of Pratice for Protective Coating of Iron and Steel Structures Against Corrosion, Britsh Standard Institution

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Measured Imperfections and Their Effects on Strength of Component Plates of A Prototype Double Hull Structure

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ABSTRACT

The U.S. Navy is currently studying the use of double hull designs in high strength low alloy (HSLA) steels for surface combatant ships. A full scale prototype double hull module was fabricated, from which multicellular box column specimens were cut for compressive tests to failure. Initial imperfections, i.e., initial plate deflections and welding residual stresses, affect the stiffness and strength of welded members. This paper describes the measurement of these imperfections and the analysis of their effects on the component plates of the cellular box specimens. Initial deflections were measured in the laboratory, where the maximum values did not exceed the Navy's guidelines or proposed values of several researchers. Residual stresses in a box specimen were also measured in the laboratory under more controlled conditions. Using the measured imperfections, the plate arrangements were analyzed using the finite element method. The imperfections were found to reduce the stiffness and strength of the plates. The results showed that for accurate prediction of the strength of welded plates, initial imperfections must be taken into account.

INTRODUCTION

Many double hull ship designs consist of twin skins of plating wrapping around the ship bottom, sides and, optionally, the main deck. The nearly parallel plates are separated and stiffened by longhudinal web girders that span between transverse bulkheads. Other transverse components are eliminated, which creates a simple unidirectional structure in the longitudinal direction. The U.S. Navy is currently studying the implementation of an advanced double hull design for surface combatant ships (1). In the commercial sector, product oil earners and tankers have already been built in Japan and Korea (2,3). Some of the reasons for considering double hull ship construction include: a simplified and unidirectional structural system that facilitates automated welding and fabrication techniques; inherent strength for improved ship survivalibility in collision or combay; and fewer areas of discontinuities and complex welded details that could give rise to fatigue and fracture problems. Figure 1 shows the difference between conventional and double hulls of ships.

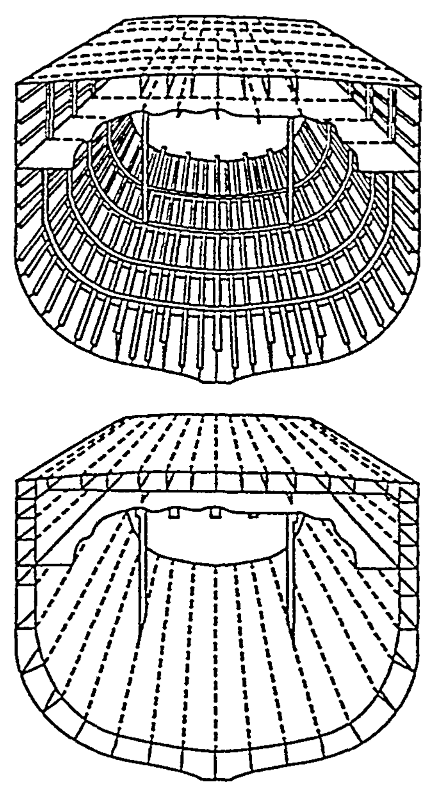

Figure 1: Conventional and advanced double hull designs (1)

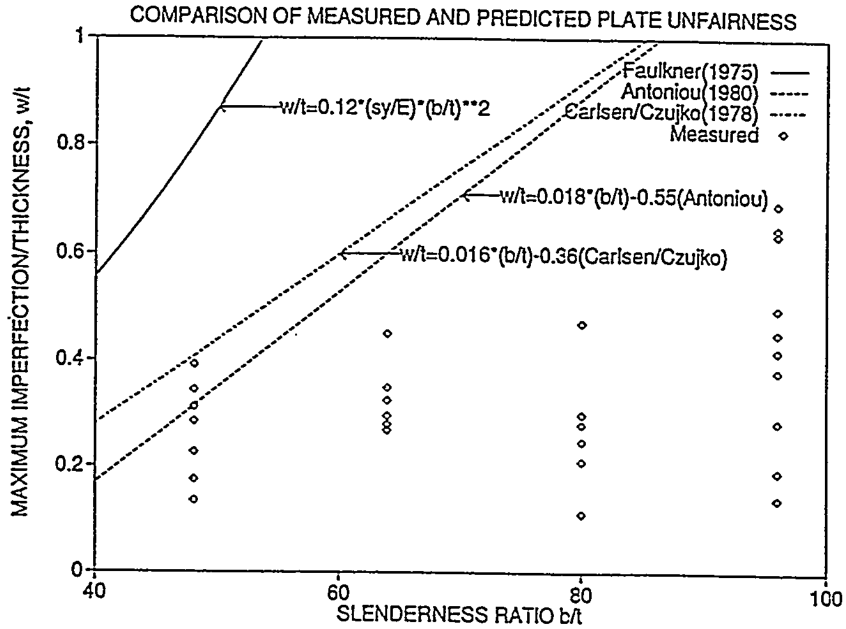

Figure 2: Maximum initial plate deflections

Longitudinal bending of a ship hull gives rise to compressive loads on the cellular components of a double hull. Hence the compressive Stability of these components, in conjunction with lateral hydrostatic presure loads, needs to be considered in design. For practical ranges of plate slenderness ratios, local plate instability will occur first, which in turn affects the stiffness and strength of the cellular beam-columns spanning between transverse bulkheads, in a coupled local-flexural type of overall member failure. It follows, therefore, that the behavior of the component plates must be determined before the overall behavior of the box beam-columns can be studied. Among other factors, local plate behavior is influenced by plate initial imperfections, distortion from the welding process, and welding residual stresses

This paper considers the effects of these two factors on local plate strength and stiffness. The measurement of these imperfections is discussed, and results from the finite element analysis using these measured imperfections are presented.

INITIAL PLATE DEFLECTIONS

Initial plate deflections are a result of various factors, such as the transverse shrinkage of longitudinal edge welds, and handling during the fabrication of the welded structure. Real plates are therefore not perfectly flat. These kinds of deviations from the flat surface (or residual stresses, see following section) suggest a load deflection rather than a buckling problem. In addition to the amplitude of the initial deflection, the longitudinal profile in relation to the plate aspect ratio has an effect on the behavior of the plate. Carlsen and Czujko (4) have shown that the presence of non-elastic buckling modes in the total modal content of the imperfections will always have a strengthening effect on a rectangular plate. However, for design purposes some degree of preferred, elastic buckling mode pattern in the initial deflections must be assumed.

Therefore, in order to assess the effect of initial deflections on plate strength, the initial deflections of each component plate of the multicellular box specimens were measured. The length of the specimens was 182.9 cm (6′) and the cross section consisted of single, double or triple box cells. Square cells were either 457 mm by 457 mm (18″ by 18″) or 914 mm by 914 mm (36″ by 36″), while rectangular cells were 914 mm by 762 mm (36" by 30") or 610 mm by 762 mm (24″ by 30″). The nominal plate thickness was 9.5 mm (3/8″), giving rise to plate width to thickness ratios of 48, 64, 80 and 96. Plate initial deflections of

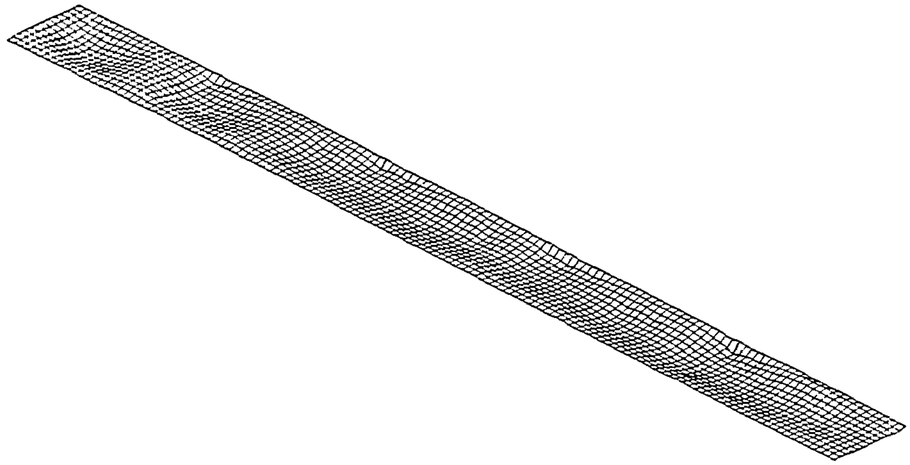

Figure 3: Typical measured out-of-flatness profile for a plate

the test specimens were measured using an aluminum frame with magnetic pads at each end. The function of the pads was to secure the frame to the longitudinal edges of the specimen while the readings were taken. Dial gauges were attached in between the pads and at regular spacings of 228.6 mm or 114.3 mm (9" and 4 1/2"), in order to take readings of the plate surface profile. The reference readings for the dial gauges were first obtained by setting the frame against a flat, milled surface. The measurements commenced at one end of the specimen at the first station, where a series of dial gauge readings were taken across the specimen width. Then the frame was moved to the next station, secured, and readings were taken again. The whole process was repeated until the last station at the other end of the specimen was reached.

The results of the measurements are shown in Figures 2 and 3. In Figure 2, the maximum measured initial deflections as a function of the plate slenderness ratio were plotted and compared to several equations for estimating maximum plate imperfection for a given plate, as proposed by Carlsen and Czujko, (4) Faulkner, (5) and Antoniou (6). The actual measured plate imperfections ranged from 3 to 12 mm (O. 12 to 0.47"), and were below the predictions of the three equations. Faulkner's equation is quadratic and the impetiections increase rapidly with the slenderness ratio. Carlsen and Czujkos', and Antoniou's linear equations show better agreement with the measured values. Measured values were also within the U.S. Navy guidelines for maximun allowable unfairness in ship plating as stipulated in MIL-STD-1689SH - Welding, Fabrication and Inspection of Ship structures.

Figure 3 shows the random surface of one of the component plates of the specimens. Measured profiles were fitted to a double sine series, Equation (1) below, using least squares regression analysis.

$$w = \sum_{i=1}^{m}\sum_{j=1}^{n} A_{ij}\sin\left(\frac{i\pi x}{a}\right)\sin\left(\frac{j\pi y}{b}\right) \quad \mathbf{(1)}$$

In general the surface profiles are quite random in nature, although in a few cases, the first longitudinal mode of deflection, i.e., a single longitudinal half wave, predominates. For design purposes it would be impractical to measure actual imperfections, so some conservative procedure, such as the proposed equations mentioned above, would be used.

WELDING RESIDUAL STRESSES

Residual stresses due to welding were measured in a single cell specimen, The stresses were measured using the sectioning method, in conjunction with a 25.4 cm (10") Whittemore

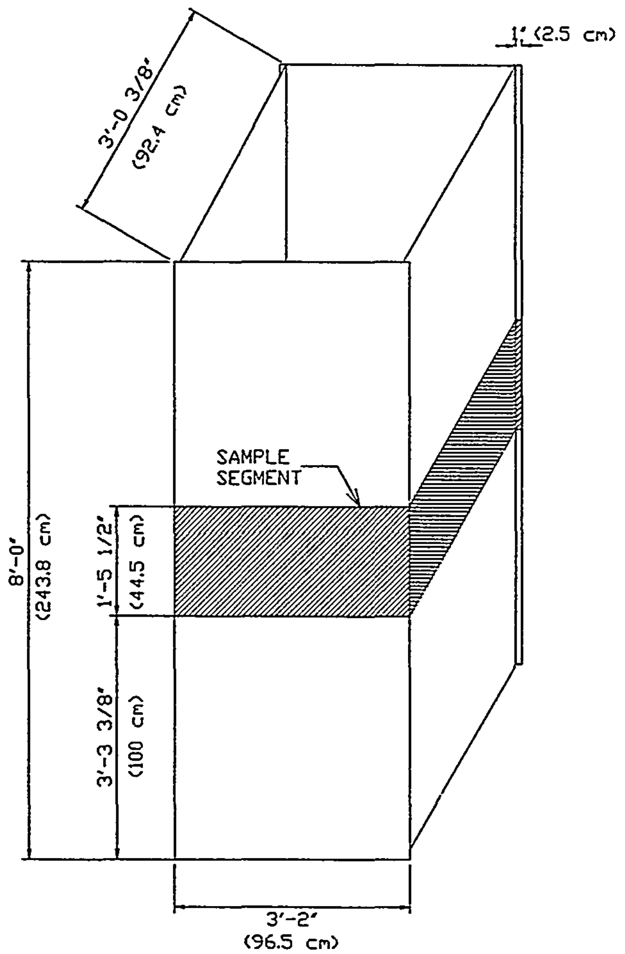

Figure 4: Residual stress test sample segment

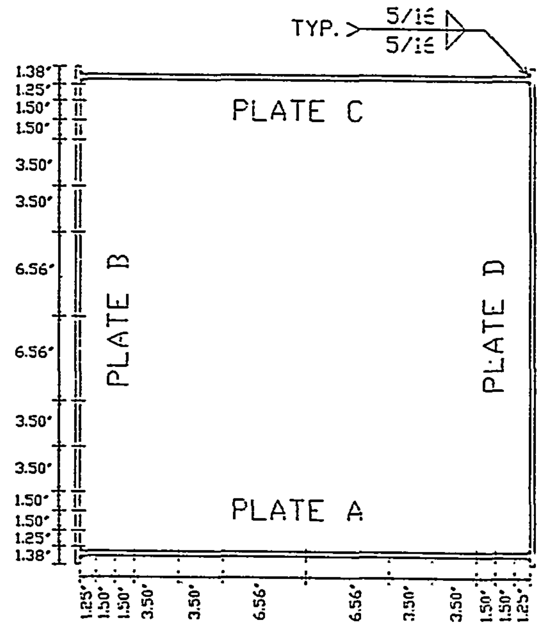

Figure 5: Dissection marks for strips used for residual stress measurements

gauge; the sectioning method was also used in conjunction with strain gauges. A test segment of 44.5 cm (1' 6") in length was removed from the single cell specimen (Figure 4) and used to measure the residual stresses by cutting it into strips. Fillet welds were placed on both sides of the plates to join them (Figure 5). Figure 5 shows the locations where Plates A and B of the segment were cut into strips. Plates C and D had similar cut patterns. In all plates, thinner strips were cut near the welds where a significant gradient in residual stresses was anticipated. The middle strips of each plate were wider, where a more constant residual stress was anticipated. Prior to cutting the segment into strips, a reference strain measurement ε_0 was taken. Strain gauges allowed a direct strain reading from each gauge. The Whittemore gauge, a mechanical device having a 25.4 cm gauge length, required two small holes to be drilled in each strip in order to take strain readings. These holes were drilled at the gauge length of 25.4 cm, centered in the middle of the strip. After placing the instrument and seating it in a pair of drilled holes in a strip, a reference reading was obtained for the strip by averaging three Whittemore measurements. A temperature reference reading was also taken, in order to minimize the effects of any temperature fluctuation of the steel during the measuring period. A liquid coolant was applied to the steel to dissipate any heat created from the cutting process; this way, any secondary residual stresses due to thermal expansion were reduced. Additional strain measurements ε_f were taken after the strips were cut. The difference between these and the reference readings ε_0 provided the residual stresses σ_{res}

$$\sigma_{res} = E(\varepsilon_f - \varepsilon_0) \qquad (2)$$

where E is Young's Modulus, 203.4 GPa (29,500 ksi).

Residual stress measurements were taken on both sides of all four plates. Figure 6 shows the residual stresses measured on the outside of the plates using the Whittemore gauge. The Whittemore gauge results show a nearly constant compressive residual stress distribution over the middle portion of each plate, with a high value of

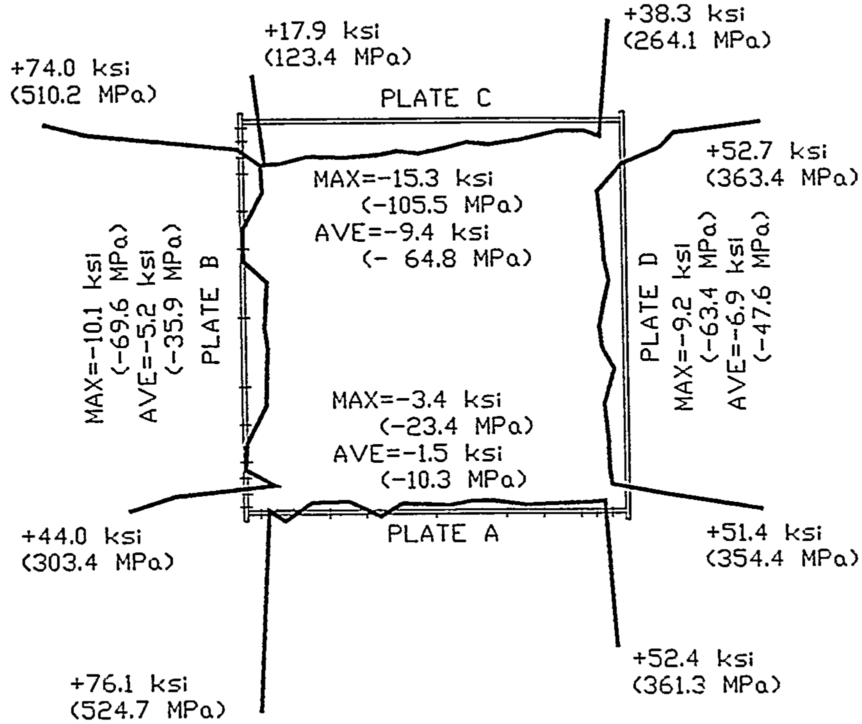

Figure 6: External Surface Longitudinal Residual Stress Distribution-Whittemore Gauge

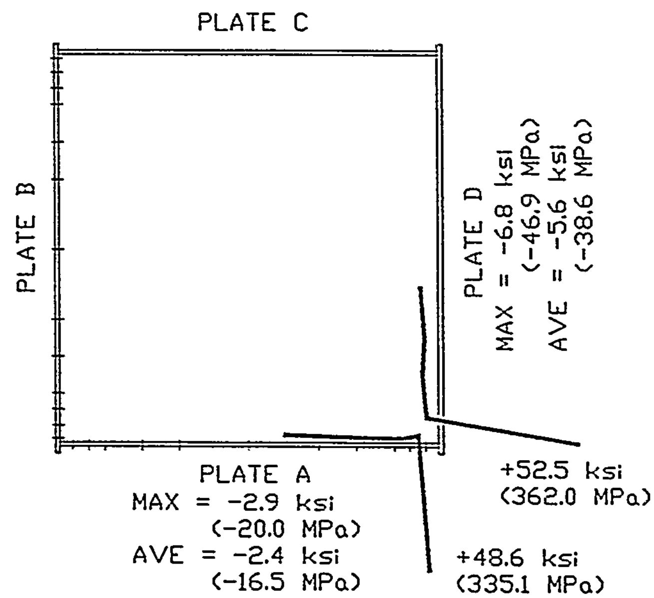

Figure 7: External Surface Longitudinal Residual Stress Distribution-Strain Gauges

tensile residual stress existing at the edges of each plate near the locations of the welds. The residual stress measurements based on the strain gauge reading are shown in Figure 7. Only a portion of plates A and D were strain gauged, as indicated by the location of the results shown in this figure. The strain gauge results agree closely with the Whittemore results, which were taken at similar locations

From the measured residual stresses of each plate, an idealized rectangular pattern of uniform tensile stresses up to yield strength σ_y along the

Plate	Average σ_{rc} MPa	η
A	48.3	3.46
B	52.5	3.74
C	64.7	4.53
D	49.5	3.54

Table I: Values for σ_{rc} and η from the longitudinal residual stress distribution

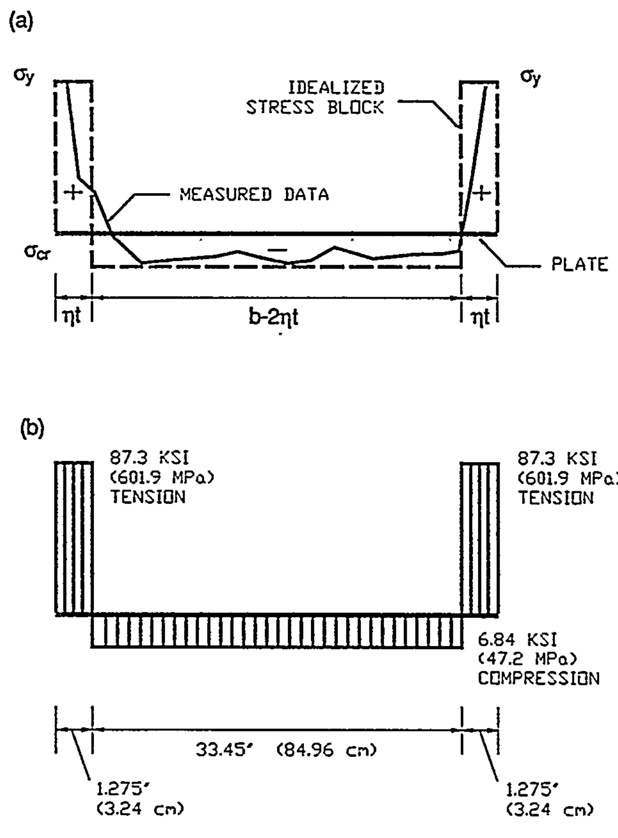

Figure 8: Measured and idealized pattern of longitudinal residual stress, Plate A

longitudinal edges of the plate was calculated, balanced by uniform compressive stress σ_{rc} over the middle strip. For each plate, the compressive stress was averaged over the middle strip of the

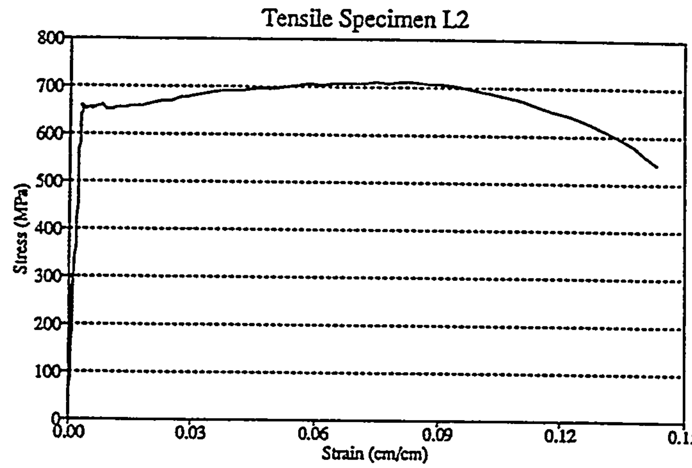

Figure 9: Representative stress strain curve for HSLA-80 tensile coupons

plate. The width of the tensile edge strips was then determined from equilibrium of the residual forces (Figure 8). The computed values of the tensile width parameter, η, was found to vary from 3.46 to 4.53 for the four plates (A, B, C, D) which formed the cell of the residual stress test segment (Table I). Faulkner (5) has recommended values of η from 3.0 to 4.5 for ship plating.

FINITE ELEMENT ANALYSIS

The component plates of the cellular box specimens were analyzed by the finite element (FE) method. The actual measured initial plate deflections, and idealized residual stresses (where η=3.81), were used in the analysis. The plates were modeled with midsurface thin shell elements using a large displacement formulation with material plasticity. Since the actual initial geometric imperfections were used, there was no plate symmetry and hence all the plates were modeled whole. A bilinear kinematic hardening material model was used together with the von Mises yield criterion. Based upon the results of tensile coupon tests, the average yield strength σ_y was equal to 600 MPa (87 ksi) and the strain hardening modulus E_{st} was equal to 1195 MPa (175 ksi). Figure 9 shows a typical stress strain curve from a coupon test performed on HSLA-80 steel.

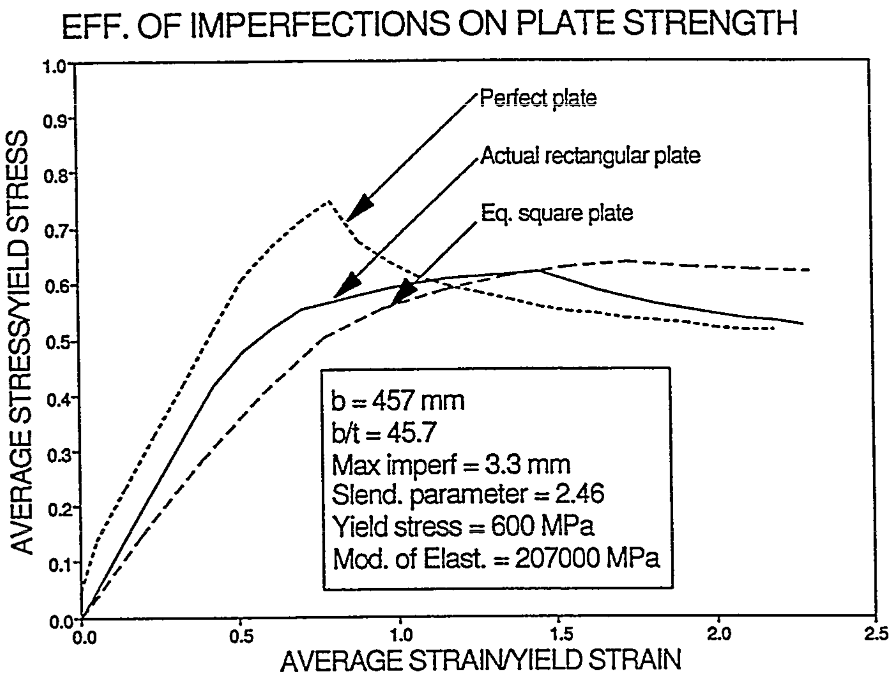

Figure 10: Comparison of load shortening curves, b/t = 45.7

b (mm)	$\frac{b}{t}$	$\frac{\sigma_{rc}}{\sigma_y}$ (η=4)	$\frac{w_{max}}{b}$	Maximum Strength		
				Square Plate	'Perfect' Plate	Actual Plate
457	45.7	0.200	0.0072	0.6332	0.7479	0.6174
914	92.5	0.091	0.0072	0.3946	0.5548	0.3825

Table 11 Comparison of maximum plate strengths

The residual stresses were entered directly into each element as initial residual strains. The idealized rectangular pattern was assumed to remain constant over the length of the plate except near the ends, where it linearly decayed to zero over a length of one plate width. Boundary conditions were taken to be simply supported and unrestrained along the longitudinal unloaded edges, and simply supported along the loaded edges. Uniform edge compressive loading was applied by means of prescribed uniform shortenings of the plate from one end, and the total load was obtained from the reactions at the other end.

Figures 10 through 13 show the results of the finite element analyses for two rectangular plates with nominal slenderness ratios b/t equal to 48 and 96, respectively. The nominal aspect ratios a/b are equal to 4 and 2. Figures 10 and 11 compare the load shortening curves for the actual plate, the corresponding "perfect" plate with no residual stresses and initial deflections, and also the corresponding square plate with the same residual stresses and amplitude of initial deflection as the **actual** plate. The imperfection profile for the square plate was taken to be single half waves in both directions. In both plates, it can be seen that plate imperfections have a marked influence on the stiffiess and strength of the plates the influence is also greater for the more slender plate compared to the less slender (stockier) plate. Table 11 lists the maximum strengths of the plates, where it is seen that the percentage strength reduction due to the combined effects of initial deflections and welding residual stresses is about 30% for the slender plate, compared to 1690 for the stockier plate. The imperfections also reduced the gradient of the unloading portion of the curve in the case of the stockier plate, as shown in Figure 10. The load shortening behavior of rectangular plates is often conservatively assumed to be similar to that of an

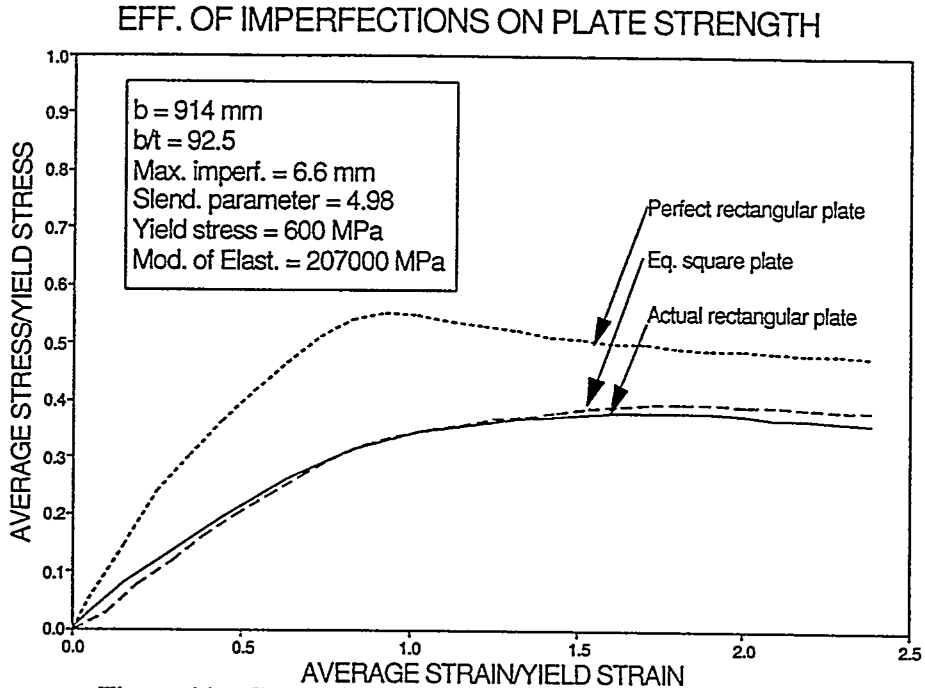

Figure 11: Comparison of load shortening curves, b/t = 92.5

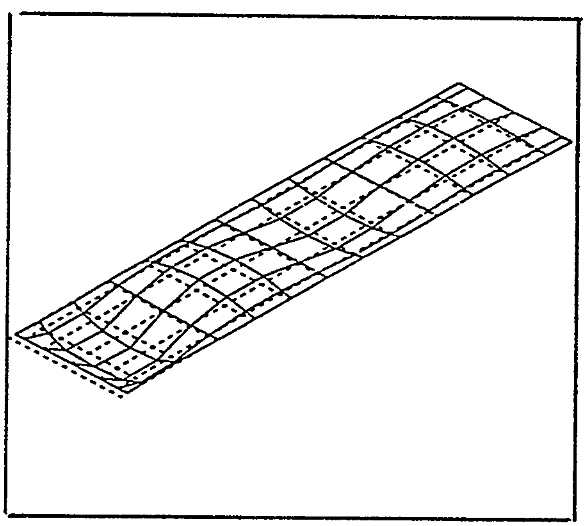

Figure 12: Deflected shape, b/t = 45.7

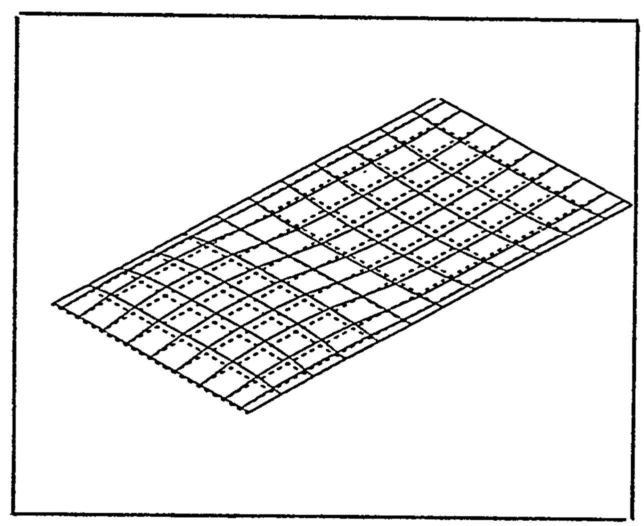

Figure 13: Deflected shape, b/t = 92.5

equivalent square plate. The figures show that the square plate curves are less stiff than the actual rectangular plate curves; peak strengths also do not differ significantly. Figures 12 and 13 show the deformed shape of the plates where the number of half waves formed is clearly seen to be 4 and 2.

The maximum strengths of all the separately analyzed plates of the test specimens (see Table III) are plotted and compared with seeral design equations in Figure 14. The design curves are the Frankland (7) curve which is used by the U.S. Navy, and the Faulkner (5) curve. The latter is plotted for two cases; with and without residual stresses. The elastic buckling curve is also shown for comparison. Frankland's equation gave good predictions at the higher slenderness ratios, but overpredicted somewhat for the stockier plates (b/t=48 and 64). By contrast, all the data points

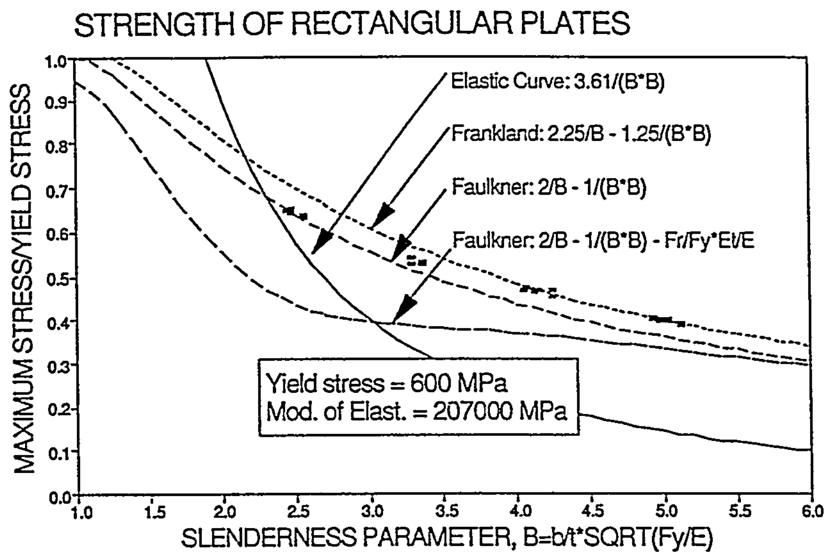

Figure 14: Comparison of FEM plate results with plate design equations

$\beta = \frac{b}{t}\sqrt{\frac{\sigma_{max}}{\sigma_y}}$	$\frac{\sigma_{max}}{\sigma_y}$	$\beta = \frac{b}{t}\sqrt{\frac{\sigma_{max}}{\sigma_y}}$	$\frac{\sigma_{max}}{\sigma_y}$
2.445	0.6490	4.117	0.4625
2.445	0.6494	4.120	0.4640
2.445	0.6496	4.125	0.4715
2.461	0.6461	4.147	.0.4704
2.461	0.6528	4.147	0.4711
2.461	0.6426	4.249	0.4549
2.553	0.6334	4.249	0.4676
2.553	0.6345	4.927	0.4050
2.553	0.6371	4.927	0.4002
3.426	0.5283	4.981	0.3983
3.426	0.5417	4.981	0.4000
3.426	0.5400	4.981	0.4002
3.371	0.5298	5.029	0.3984
3.371	0.5339	5.029	0.4008
3.371	0.5322	5.116	0.3876
4.055	0.4690	5.116	0.3906
4.060	0.4758	5.116	0.3922
4.114	0.4711		

Table III: Maximum strengths of rectangular plates by finite element analysis

were above the Faulkner stress-free plate equation. The Faulkner equation for welded plates is seen to give very conservative predictions compared to the finite element results. The results indicate that the Frankland equation is suitable, while the Faulkner equation seems to be the best for estimating plate ultimate strengths.

CONCLUSIONS

Initial imperfections have been shown to affect the behavior of welded plates. The actual measured initial deflections of the welded component plates of a prototype double hull structure were in the range of 3 to 12 mm (0.12 to 0.47"), and within specifications. Measured residual stresses in the component plates of the welded module showed the typical pattern of narrow edge strips of high tension, and a wide middle strip of low, fairly uniform compressive stresses. The maximum strengths of welded plates were reasonably predicted by the Frankland and Faulkner stress-free equations. Results also showed that equivalent square plate load shortening behavior can be used to represent the behavior of the corresponding rectangular plate.

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REFERENCES

1. Beach, J. E. (1990) "Advanced Surface Ship Technology," ASNE Symposium 1990, pp 89-112.

2. Okamoto, T., Hori, T., Tateishi, M. Rashed, S. M. H., and Miwa, S. (1985) "Strength Evaluation of Novel Unidirectional Girder-System Product Oil Carrier by Reliability Analysis," Trans. SNAME, Vol. 93, pp 1-18.

3. Park, J. K., Kim, D. H., Bong, H. S., Kim, M. S., and Han, S. K. (1992) "Deterministic and Probabilistic Safety Evaluation for a New Double-Hull Tanker with Transverseless System;' Procs. Annual Meeting 1992, SNAME, New York.

4. CarIsen, C. A. and Czujko, J. (1978) "The Specification of Post-Welding Distortion Tolerances for Stiffened Plates in Compression," The Structural Engineer, Vol. 56A, No. 5, pp 133-141.

5. Faulkner, D. (1975) "A Review of Effective Plating for use in the Analysis of Stiffened Plating in Bending and Compression," J. Ship Research, Vol. 19, No. 1, pp 1-17.

6. Antoniou, A. C. (1980) "On the Maximum Deflection of Plating in New Ships," J. Ship Research, Vol. 24, No. 1, pp 31-39.

7. Parlane, A. J. A. (1976) The Determination of Residual Stresses: A Review of Contempormy Techniques, The Welding Institute, Abington Hall, Abington, Cambridge, CBl 6AL, U.K.

8. Frankland, J. M. (1940) "The Strength of Ship Plating under Edge Compression," U.S Experimental Model Basin Report No. 469, Washington, D.C.

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